

PB86-219193

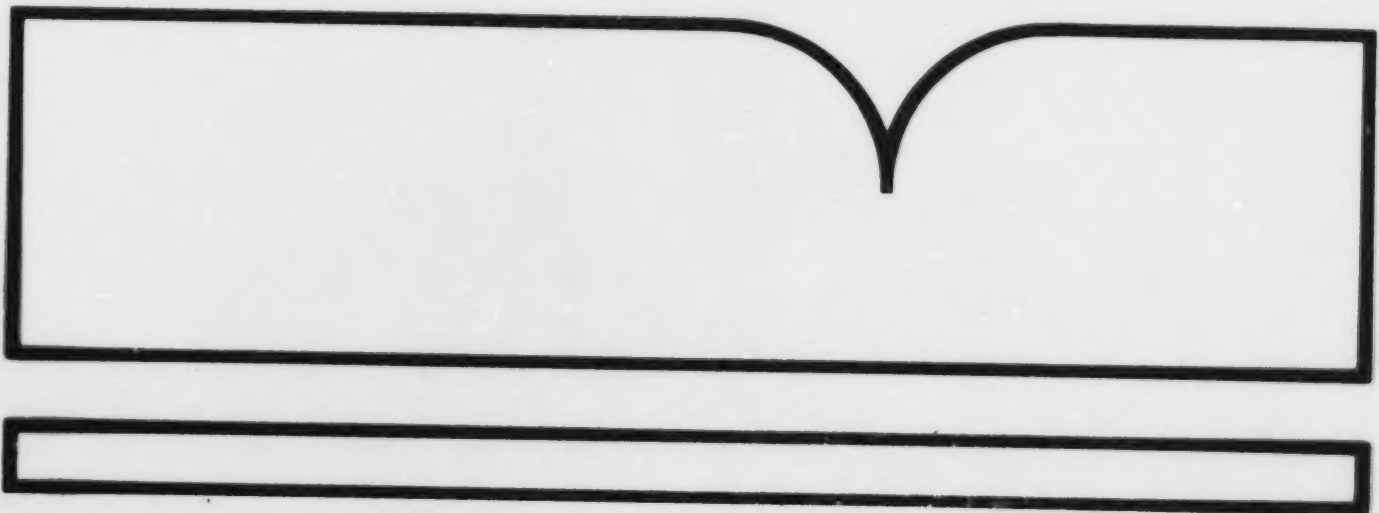
Proceedings of an Engineering Foundation
Conference on Management of Atmospheres in
Tightly Enclosed Spaces Held at
Santa Barbara, California on October 17-21, 1983

American Society of Heating, Refrigerating and
Air-Conditioning Engineers, Inc., Atlanta, GA

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

Jul 86



U.S. Department of Commerce
National Technical Information Service
NTIS

Proceedings of
An Engineering Foundation Conference on
Management of Atmospheres in
Tightly Enclosed Spaces

October 17-21, 1983
Santa Barbara, California

J. E. Janssen, Conference Chairman
American Society of Heating, Refrigerating
and Air Conditioning Engineers, Inc.
1791 Tullie Circle, N. E.
Atlanta, Georgia 30329

EPA Purchase Order 4DO435NAEX

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Air and Energy Engineering Research Laboratory
Research Triangle Park, North Carolina 27711

Cosponsored by:

Engineering Foundation
American Society of Heating, Refrigerating
and Air Conditioning Engineers, Inc.
U. S. Department of Energy
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AIR AND ENERGY ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

TECHNICAL REPORT DATA (Please read instructions on the reverse before completing)		
1. REPORT NO. EPA/600/9-86/020	2.	3. RECIPIENT'S ACCESSION NO. PB86 219193/AS
4. TITLE AND SUBTITLE Proceedings of an Engineering Foundation Conference on Management of Atmospheres in Tightly Enclosed Spaces	5. REPORT DATE July 1986	
	6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) J. E. Janssen, Conference Chairman	8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. 1791 Tullie Circle, N. E. Atlanta, Georgia 30329	10. PROGRAM ELEMENT NO.	
	11. CONTRACT/GRANT NO. EPA Purchase Order 4DO435NAEX	
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development* Air and Energy Engineering Research Laboratory Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED Proceedings; 10/17-21/83	
	14. SPONSORING AGENCY CODE EPA/600/13	
15. SUPPLEMENTARY NOTES AEERL project officer is W. Gene Tucker, Mail Drop 54, 919/ 541-2746. (*) Cosponsored by the Engineering Foundation, ASHRAE, DOE, and EPA. Conference held in Santa Barbara, CA, October 17-21, 1983.		
16. ABSTRACT The proceedings document presentations made at the Engineering Founda- tion Conference, held in Santa Barbara, CA, October 1983, to assess the state of knowledge about management of atmospheres in tightly enclosed spaces and to discuss the newer methods for mitigating indoor pollutants. Specific objectives of this confer- ence were the assessment of the state of knowledge for consideration in the revision of ASHRAE Standard 62-1981 and providing background information for both DOE and EPA in planning their programs for improving indoor air quality. Presentations were: Some Existing Indoor Air Quality Problems; Formaldehyde Release from Build- ing Materials; Formaldehyde Emissions from Combustion Sources and Solid Formal- dehyde Resin Containing Products; Ventilation and Body Odor; Effect of Ventilation on Passive Smoking Risk in a Model Workplace; The Impact of Building Codes and Regu- lations on Indoor Air Quality; Substitute Materials; Psychological Factors in the Im- pacts of Indoor Air Quality on People; Radon Concentrates and Ventilation Rates in Eastern Pennsylvania Houses; Electronic Air Cleaners and the Indoor Environment; Air Cleaning with Granular Adsorbents; Air Mixing Efficiency; Air Infiltration and Indoor Air Quality; and Effects of Different Ventilation Parameters on Indoor Pol- lutants.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution Ventilation	Pollution Control	13B 13A
Atmosphere Contamination Control	Stationary Sources	06K, 14G
Residential Buildings Smoking	Indoor Air	13M
Formaldehyde Building Codes	Body Odor	07C 05D
Construction Materials Radon		13C 07B
Combustion Psychological Effects		21B 05J
Adsorbents		11G
18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 147
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

ACKNOWLEDGEMENTS

Ambrose E. Swasey, a successful machine tool manufacturer endowed the Engineering Foundation in 1914 "for the furthering of research in Science and Engineering and for the advancement of the profession of engineering and the good of mankind". Deterioration of the indoor atmosphere as a result of some energy conservation measures and the use of some new materials in buildings has become a problem of growing concern. Better data are needed for modification of the ASHRAE Ventilation Standard. The Conference Committee is grateful to the Engineering Foundation, the American Society of Heating, Refrigerating, and Air Conditioning Engineers, the U.S. Department of Energy and the U.S. Environmental Protection Agency for sponsoring this conference and for their financial support. The committee is also grateful to the authors/participants for their valuable presentations and spirited discussions.

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Any opinions, findings, conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the conference sponsors.

ISBN 0-910110-40-9

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Executive Summary

Management of Atmospheres in Tightly Enclosed Spaces

J.E. Janssen, P.E.

Indoor air pollution is a major problem in buildings that is rapidly being recognized. An Engineering Foundation Conference was held in Santa Barbara October 1983 to assess the state of knowledge about management of atmospheres in tightly enclosed spaces and to discuss the newer methods for mitigation of indoor pollutants. Approximately 25 invited speakers representing most of the groups doing significant work in this area and 20 interested colleagues attended. ASHRAE sponsored the conference with interests stemming from its Standard 62-1981, "Ventilation for Acceptable Indoor Air Quality". DOE and EPA were co-sponsors with interest in energy requirements for the ventilation of buildings and for better definition of indoor air quality problems and related control technology. Specific objectives for this conference were on assessment of the state of knowledge for consideration in the revision of ASHRAE Standard 62-1981 and background for both DOE and EPA in planning their programs for improving indoor air quality.

Coordination of the conference arrangements was managed by the Engineering Foundation. This foundation was endowed with a grant from Ambrose E. Swasey (a success as a machine tool manufacturer) in 1914 "for the furthering of research in Science and Engineering and for the advancement of the profession of engineering and the good of mankind". Conferences of this type are held on a variety of specific topics at frequent intervals.

The conference program was divided into two parts; the first was devoted to defining the major pollution problems in buildings, and the second with assessing the state of the art of control techniques. Mr. James Frazier, National Research Council, discussed several indoor pollutants and the relationship of exposure, dose, and advance health effects and the need for documentation in Standard 62-1981. Many of the pollutants in the indoor air result in an accumulative dose from exposure to various sources of them. Often the very young and the very old spend most of their time indoors in the home. Workers, on the other hand are exposed in the work place environment 8 hours a day, 5 days a week. Thus, the dose accumulated by an individual may be substantially greater in the home even though the contaminant levels are much lower than in the work place or in the ambient air. Thus, the work place threshold limit values (TLV's) cannot be used in the home as limits for exposure in the same way they are used in the work place. Standard 62-1981 has used a reduction factor of 1/10 of the TLV for several pollutants. The rationale for using this factor was based on the fact that there are four times as many hours of exposure in the indoor environment as in the work place. The safety factor of 1/10 the TLV concentration was introduced to account for the fact that infants and the aged may be less able to tolerate stress induced by contaminants. This is an uncertain practice that has no data base upon which the extrapolation of work place TLV's can be proven to be acceptable. There is a critical need to accurately and objectively assess the health risks to all occupants, thus, exposed to known hazardous indoor pollutants. It was also noted that the human nose is most sensitive to the presence of odorous pollutants and this recognition can lead to complaints about indoor pollution. It is important to have knowledgeable people with appropriate instruments who can follow up on complaints and obtain the true facts about the nature, character and concentrations of the pollutants.

J.E. Janssen, Principal Engineering Fellow, Honeywell Inc. Technology Strategy Center, Roseville, MN.

Greg Traynor, Lawrence Berkeley Laboratory, reported on the use of unvented combustion systems. Kerosene and gas fired space heaters can be divided into two classes, radiant and convective. Radiant heaters cool the flame and reduce nitrogen oxide emission. This flame quenching tends to produce more carbon monoxide, however. Convective heaters tend to produce less carbon monoxide but more nitrogen oxides. Carbon monoxide emissions tend to decrease as operating time increases. This is probably due to a gradual increase in flame temperature with operating time.

Wood stoves, even though they are vented, tend to smoke and leak combustion products into a home, especially during start-up. Ventilation rates for unvented combustion systems need to be established.

Much progress has been made in reducing formaldehyde emission rates from plywood and particle board according to C. Beat Meyer, Professor of Chemistry, Washington State University. Differences greater than ten-fold in the formaldehyde emission from different manufacturer's particle boards have been measured. The molar ratio of the reactants in urea formaldehyde resins has a marked influence on the amount of unreacted formaldehyde. Manufactured homes (mobile homes, etc.) may contain as much as a pound of unreacted formaldehyde.

While there is a 5% cost penalty and some problems with supplies of particle board and plywood with low formaldehyde emission rates, it appears that the industry is working quietly to reduce formaldehyde emission rates in manufactured homes. It also appears that the 0.1 ppm limit for formaldehyde recommended is achievable and is reasonable based on documented comfort criteria.

Dr. Thomas Mathews, Oak Ridge National Laboratory, also discussed the emission of formaldehyde from wood products. He has measured emission rates as a function of temperature and humidity in a special teflon lined chamber. Teflon was required to minimize the collection of formaldehyde molecules on the walls of the chamber. Emission rates were found to be a function of the thickness of the material (e.g. chipboard, plywood, etc.), the temperature, the humidity, and the ambient concentration of vapor in the air. Models have been developed for describing internal formaldehyde concentration gradients in terms of temperature, humidity and ambient formaldehyde vapor pressure. The interaction of ambient conditions with the materials produces variable emission rates that upset a simple ventilation model based on a constant emission rate. Increasing the ventilation rate to reduce ambient formaldehyde concentration tends to increase the emission rate. Thus, the reduction in ambient formaldehyde concentration is not linear with respect to ventilation rate. Other measures such as more optimum formulation of the adhesives or sealing (passification) of the surfaces may be needed also. Manufacturers appear to be making progress in this direction.

Dr. P. Ole Fanger from the University of Denmark described work on ventilation to control odor. His group has been repeating Yaglou's classic work carried out in the early 1930's. Fanger has used relatively large groups of college students in larger rooms than Yaglou. Unlike Yaglou, Fanger finds no correspondence between ventilation rate and space ($\text{ft}^2/\text{person}$) for odor control. Both Fanger and W. Cain, J.B. Pierce Laboratory, Yale University, have found a small correlation between odor dissatisfaction and carbon dioxide level. There is greater dissatisfaction as the CO_2 rises. Both Fanger's and Cain's experiments have been carried out with visitors, i.e., the subjects were brought from a "clean" space into the test space, where conditions had been established by other occupants, and asked to vote immediately on acceptability. The present outdoor air flow rate of 2.5 L/S specified in Standard 62-1981 will satisfy only 50% of the visitors. A flow rate of 8 L/S (16 cfm) is needed to satisfy 80% of the visitors. Adapted occupants in a space (i.e., those who have been there for 15 minutes find 2.5 L/S generally acceptable). Thus, it appears the ventilation standard should consider the difference between visitors and adapted occupants in various applications.

Fanger also discussed some of Cain's data on smoking. Cain has found that 80% acceptance will require 120 m^3/hr (33.3 L/S or 70 cfm) of ventilation per cigarette. With the normal smoking rate of 0.6 cigarette per occupant (both smokers and non-smokers, included) this corresponds to a required ventilation rate of around 20 L/S per occupant, not far from the 17.5 L/S per occupant (35 cfm) recommended in 62-1981. J. Repace pointed out that people with allergic diseases respond to tobacco smoke differently and are generally much more sensitive.

Dr. James Repace, EPA, reviewed the history of the knowledge of smoking dangers. The first report of the Surgeon General implicating tobacco as a cause of cancer came out in 1964. By 1979 there was overwhelming knowledge of the health risk related to tobacco smoke. Approximately one-third of the adult population smoke two cigarettes/hour at 10 minutes per cigarette. Thus, 1/3 smoking 1/3 of time means 1/9 or 11% of population is always smoking. Repace has related health risks to ventilation rate and finds that 20 cfm minimum outdoor air produces a health risk of about 1.5×10^{-3} . This is higher than an ideal risk of 10^{-5} which is realized for many dangers, but is less than the risk accepted for hazards such as automobile travel. The value of 20 cfm is about at the point of diminishing returns. A risk of 10^{-5} would require 985 cfm of outdoor air per person. Ignoring the smoking risk and using the minimum outdoor air flow rate of 5 cfm raises the risk to a clearly unacceptable level. Repace expects to publish his recommendations for control of tobacco smoke in 1984.

Robert Trietman, Harvard also discussed the problem of "side smoke". Smokers tend to hold their cigarettes away from their own person when not actually inhaling. The Harvard Air Pollution/Lung Study found that although 1/3 of the adult population smokes, between 50 and 75% of the children in the study live in homes where at least one person smokes. These children show increased pulmonary disease and differences in lung function. It has been found that in Japan non-smoking women who lived with husbands who smoke have twice the cancer risk as those who live with non-smoking husbands. Studies in Greece showed a 2.4 times risk increase when husbands smoked 1 pack of cigarettes per day and 3.4 times increase for two packs per day. There are insufficient data to reveal any differences in health risk associated with the type of heating system or use of electronic air cleaners.

Dr. A. (Tony) Nero of Lawrence Berkeley Laboratory discussed the radon problem. He feels the present standard, while recognizing radon as a contaminant of concern, over simplifies the control problem. The radon concentration may be somewhat independent of infiltration since stack effect which increases infiltration also tends to suck radon from the soil into the structure. He also finds that radon concentration in water does not necessarily correlate with the usual distribution in the soil. Filters that remove particulates do reduce radon progeny. The risk factor associated with radon is about 2×10^{-4} per working level month (WLM). One pico curie per liter of air is equivalent to 0.2 WLM. Nero feels that ventilation alone is insufficient for proper control of radon.

James Jaax of Johnson Space Center discussed the special problems of creating an acceptable spacecraft environment. Temperatures around 78°F with relative humidity of 50% or less have been found acceptable. The absence of gravity has no effect as long as forced circulation is maintained. Air circulation rates of around 25 ft/min are desirable. (this is consistent with change from natural to forced convection over the human body in an earth-bound environment.)

Carbon dioxide levels of 1% have been used in the space shuttle. Space stations are expected to be held to 0.5%. Odor is something of a problem, however, there is a build-up of trace metabolic products in the air.

Dr. Preston McNall of NBS discussed the issue of building codes in the U.S. Thirty five states have state-wide building codes. Thirty two of these are based on one of three model building codes. The Building Officials Code Administration (BOCA) code is used in the northeastern and midwestern parts of the U.S. The International Conference of Building Officials (ICBO) code is used in the western part of the U.S. And the Southern Building Code Congress (SBCC) code is used in the south. In addition 80% of the cities over 500,000 population use the model codes. These codes all use at least parts of the ASHRAE Standard 62-73. Several states are considering use of Standard 62-1981 as recommended in ASHRAE's position statement on ventilation. The codes vary considerably in their treatment of such things as tobacco smoke. The Southern code, for example, ignores tobacco smoke as a special consideration. In general, codes are enforced by review of building designs. There are no performance inspections. A few codes require a positive source of combustion air for furnaces and fireplaces, but there is little enforcement of ventilation codes in single family residences.

Dr. John Carlton-Foss discussed the relations among psychological, thermal comfort and physiological approaches to testing responses of people to environmental conditions in the laboratory or in the field. He showed the evolution of the ballots used to measure subjects' evaluations of thermal environments. He emphasized that Rohles had used a semantic differential ballot with multiple scales to do the experiments which led to the comfort zone in ASHRAE Standard 55-1981, and that a similar ballot should be used in work with comfort and indoor air quality. He said that individual differences play an important role in thermal comfort

and can be expected to play a similar role in response to pollutants in indoor air. He cited a field study in which personality was found to be the most significant factor in occupants' satisfaction or dissatisfaction with the "stuffiness" of the indoor air. The subjective responses measured with such ballots can also be quantified through measuring the impacts of indoor air pollutants on people's performance. There are specific and general effects, and he cited his recent study on seating and performance as an example of measuring the impact of general stress on performance. He cautioned that investigators should be aware of complex, and sometimes confusing, interactions among many variables, including psychological and ergonomic ones. There are methods for separating the variables, and these should be taken into consideration when designing new work, or when reviewing work that does not explicitly include them.

Dr. Harvey Sachs, National Indoor Environmental Institute, presented two papers on the subject of radon. The first was a discussion of a study of the prevalence of radon in homes in eastern Pennsylvania. His study of ten homes in one town showed that older homes tend to have lower radon than new homes due to generally lower infiltration (ventilation) rates in newer construction. Local geology is an important predictor of radon contamination. Soil permeability and source strength influence radon level in the homes. Sachs stated that there are several orders of magnitude variation in radon exposure for people living in the United States and that the radon level in a home often is an indication of soil radon level and permeability. His conclusion was that although exposure to radon in the eastern United States is relatively high, little excess lung cancer is to be expected now. The highest exposures are in the stock of new houses. The cumulative population dose will remain low for the next two decades. It would appear that this may be a time bomb waiting for the future. U.S. data on the radon problems are still sketchy.

In his second paper, Sachs described an experiment in which radon was removed from the soil under the floor slab of a house by ventilation of the soil. In one house an open unlined sump in the basement floor was sealed and fitted with an exhaust fan vented to the outdoors. This depressurized the soil under the floor and decreased the radon concentration in the basement by 90%. In a second case, a basementless, earth-sheltered house had sub-slab air ducts which brought in large amounts of radon. A partial vacuum on the perforated parameter drain pipe reduced radon concentrations by 80% without sealing the ducts. Ventilating a drain pipe around the foundation of a third house also gave an 80% reduction in radon. Depressurization of the soil under and around the foundation substantially reduced radon levels in all three cases.

Dr. Dean Baker, UCLA School of Public Health, discussed his investigations of "sick buildings" when he was health investigator for NIOSH before his present appointment at UCLA. Measurements were made by questionnaires and interviews. Efforts then were made to correlate subjective data with factors such as location inside the building and location of the building in the community; time of day, week or season; and similar variables in an effort to find possible cause/effect relationships. Specific subjective symptoms were complaints of "stuffiness" of the building environment and absenteeism caused by various illnesses attributed to the building environment. Physical measurements showed a plethora of chemical contaminants usually well below recommended concentration limits. Thermal discomfort was a common factor. The NBC building in New York City was an example. Nineteen contaminants were identified, but all were below the lowest recommended industrial limits, but use of industrial limits has been questioned. Building ventilation was not measured but was estimated to be 35% below recommended ventilation rate. Incomplete detailed measurement of all pertinent factors is a problem in much of the data on sick buildings. There is considerable interaction among chemical, physical, biological, and social factors. Acute symptoms include hypersensitivity to pneumonitis (humidifier fever) dermatitis and non-specific (sick at home) complaints. Chronic symptoms include chronic respiratory disease, neurasthenia and possible cancer. Baker said that the effects of large particles of fibrous glass, which cause dermatitis, do not correlate well with ventilation rate. Problems are often due to perception of conditions. Physical response to contaminants occurred in the first four weeks of exposure. Reports of multiple symptoms followed. Baker recommended creation of an environmental committee to deal with complaints.

David Harris, National Institute of Building Sciences, discussed mitigation of problems through the use of substitute materials. NIBS conducted a study, in 1983, to compile and organize a comprehensive list of building materials, products, and systems typically used to construct office buildings, schools, and homes for the elderly since 1970 in the Washington D.C. area. Typical activities which occur in these buildings were also listed, as were organizational reference sources for more detailed information on each subject area. The effect of these materials and activities on indoor air quality for each of the three building types will be further studied by the EPA as part of the Agency's total exposure monitoring program. While the data and analyses are far from complete, this approach appears to be a good effort to identify some sources of indoor air pollutants.

Brian Krafthefer, Honeywell, presented data showing the effect of an electronic air cleaner on radon progeny concentrations. Measurements of radon progeny in the basement of a home in Minneapolis revealed an inverse correlation with barometric pressure and a diurnal variation with temperature when the furnace was not operating and the fan and air cleaner were off. Activity levels up to about 0.03 WL, three times the limit specified in Standard 62-1981, were measured. Operation of the furnace fan reduced the peaks by 50%. Operation of the electronic air cleaner held the activity level to less than 0.005 WL, half of the recommended limit. At this level there was no apparent correlation with barometric pressure or temperature.

J. Donald Cummins, Purafil Inc., discussed the use of adsorbing and oxidizing filters. Activated carbon has a surface area of about 90 acres per pound of material. Vapor molecules coming in contact with this surface are held by Van der Waals forces. Adsorption is proportional to molecular weight. Thus, materials such as activated carbon and activated alumina are much more effective in removing large organic molecules than they are in trapping small gas molecules like carbon monoxide. Removal efficiency can be enhanced by adding reactive chemicals which combine with the trapped molecules. Potassium permanganate added to activated alumina is very effective on oxidizable vapors. The adsorbed molecules are oxidized by the permanganate. Vapors such as hydrogen sulfide and formaldehyde can be efficiently removed from air by this material. The filter medium does have a finite life, however, but the cost is often an attractive alternate to other air cleaning methods when special problems exist.

Professor Amos Turk, New York City College, discussed the five different physical process of using granular materials for air cleaning. Molecules may be physically adsorbed on the surface of porous materials such as activated carbon or alumina. The addition of various reagents can cause the adsorbed molecules (P) to be neutralized (N), oxidized (O), complexed (C), or decomposed (D).

The typical means of gas/vapor filtration with granular media are given in the table below:

<u>Pollutant</u>	<u>Possible Filtration Means</u>
Body Odor	P, N
Cosmetics	P
Plasticizers	P
Radon	P
Tobacco Odors	P, O
Fecal, Urine Odors	P, N, O, C
NO ₂ , SO ₂	P, N, O
Ozone	D
Peroxides	P, D
Ethylene	C
Mercury Vapor	C
Metal Hydrides	P, O
Fumigants (EDB)	P

Except for the decomposition of ozone or peroxides, the reagents are consumed with use, and the filtration material must be replaced or rejuvenated periodically.

Dr. James E. Woods, Iowa State University (recently joined Honeywell) discussed some of the compromises between air quality and cost. Doing nothing to humidifiers and ducts which may be wet sometimes, now introduces a prohibitive cost due to the danger of Legionnaires' disease. Rigorous maintenance and special treatments to improve indoor air quality are required. Biological contaminants are not presently spelled out in the Standard 62-1981, but should be considered. Woods also questioned the acceptability of 2500 ppm of CO₂. European and Japanese standards limit CO₂ to 1000 ppm. Woods suggested that ventilation systems might be rated as to effectiveness, perhaps on a scale of 1 to 10.

J. E. Janssen discussed the problem of ventilation or air mixing efficiency. Standard 62-1981 assumes that all of the outdoor air that is inducted into a building is effective in diluting the contaminants. Tracer gas tests and flow models show that this is a poor assumption. When the supply outlets and return inlets of a ventilating system are both located in the ceiling, as they commonly are, and if the exhaust air is taken from the recirculating air stream, as it usually is, it is possible for a significant amount of outdoor air to be inducted into the supply, bypass directly from the supply outlet to the return and be exhausted without ever mixing at the occupied level. A model has been devised to calculate this wasted ventilation. Tracer gas decay measurements at the return inlet and at the occupied level provide the needed data. Mixing efficiencies of only 50% may be common.

Robert Macriss, Institute of Gas Technology, discuss infiltration in residential structures. Infiltration is the main passive means of controlling air quality in residences. IGT data show that infiltration can vary from 0.01 to 1.0 air change per hour in a given house. IGT has procedures and a model for extrapolating single point measurements. They have found that the concentrations of contaminants from internal sources are more a function of inter-zone mixing than of infiltration rate. Both the LBL and IGT models confirm the usefulness of single cell models.

Dr. William Fisk, Lawrence Berkeley Laboratory reviewed the use of mechanical ventilation systems in residences. During the past five years, 15 to 20 thousand units per year have been sold. This is a small fraction of the homes that have been built. Mechanical ventilation is effective against both radon and its progeny. Enthalpy type air to air heat exchangers conserve humidity in cold climates but also tend to conserve dissolved formaldehyde. Air to air heat exchangers have discouraging economics. First cost may be upwards of \$500. Fan power ranges from 0.7 to 3.6 watt/cfm. Thermal efficiencies range from 50 to 70% and air flow rates range from 80 to 240 cfm. Payback periods in climates like Minneapolis range from 12 to more than 30 years. In Washington D.C. the payback period ranges from 16 to more than 30 years. Leakage between air streams reduces efficiency and cold weather operation can produce icing problems. Good maintenance is required to prevent biological contamination and a possible source of legionellosis.

E. Sterling, TDS Ltd., discussed a data base he has on air quality and ventilation in 143 buildings. Unfortunately ventilation rates were not always reported with measured contaminant levels. Sterling believes that occupancy is the best measure of contaminant load in office buildings. He also found poor correlation between the building design and actual occupancy. Since code enforcement is usually based on design it is likely that many buildings are operated well outside the recommendations of the ventilation standard.

Dr. D. Moschandreas, Illinois Institute of Technology, Research Institute, reviewed measurements of emissions from gas cooking ranges. Tests were made in a chamber with a ventilation rate of 100 cfm (consistent with Standard 62-1981). Three different ranges were tested, each in two different extremes of air/fuel mixture. One condition was a normal stoichiometric, blue-flame and the other was a yellow, diffusion flame representing a malfunctioning burner. Formaldehyde emission rates of 1200 to 8000 micrograms/hr were measured.

Tom Phillips discussed public health considerations in the development of residential building standards in California. The standard was adopted in 1978. This standard required caulking around the sole plate, around wall outlets, sealing of ducts in unconditioned spaces, and caulking around windows and doors. Outside venting of cooking ranges was recommended. This residential standard was implemented through the use of an extensive questionnaire to be answered by the building contractor. New design targets are 0.4 ach. Houses achieving 0.3 ach are to have heat exchangers and dehumidifiers. The code is the result of much testimony and compromise.

Robert Treitman, Harvard University, also reviewed experimental techniques for particulate measurements. The Harvard group has used high volume and dichotomous samplers. Aerosol mass balance instruments have been less successful for low concentrations found in residences.

Nagda, Geomet, reviewed the status of their current project with EPRI. Two "identical" 1400 sq.ft. houses have been built and are being used for studies of indoor generated pollutants. The houses are unoccupied and one is used as a control. Typical household activities such as cooking on a gas range, vacuum cleaning, and clothes laundering generate pollutants to be measured. Measurements include CO, NO_x, radon, formaldehyde, particulates, and CO₂. Infiltration is measured with SF₆ tracer gas. Carbon monoxide rose to 7.5 ppm upstairs after two hours of operation of the gas range with the furnace fan off and 5 ppm with the fan on. Sealing of the structure to achieve 40% reduction (by blower door test) had little effect on CO concentration.

Dr. P. O. Fanger, Technical University of Denmark reviewed recent studies of the effect of drafts on comfort. The test chamber consisted of a room in which subjects were exposed to air velocity fluctuations as they occur in normally ventilated spaces. Fluctuating velocities have been found to be more objectionable than steady velocities. Temperatures of 20°C, 23°C and 26°C have been investigated. Surprisingly, short haired subjects complained less than long haired. Twenty percent of the subjects felt a mean velocity of 0.15 m/s (30 ft/min) as uncomfortable at 20°C. This indicates a need to review the Air Diffuser Performance Index which defines 0.35 m/s (70 ft/min) as the threshold of discomfort.

The final session of the conference addressed the questions of how the ASHRAE Ventilation Standard 62-1981 should respond to new data. It was suggested that the Air Quality Procedure could be based on health risk. People accept personal risk of 10⁻¹ to 10⁻². Lifetime smoking risk is 10⁻¹ and lifetime risk for driving an automobile is 10⁻². Occupational risks are generally in the range of 10⁻² to 10⁻³. Environmental risks are generally less than 10⁻³ and some are as low as 10⁻⁵. The current level of risk in the home is in the range of 10⁻² to 10⁻³. It is probably impractical to try to reduce the home risk below 10⁻³. Commercial buildings have risk factors in the range of 10⁻³ which may be a reasonable level. Risk factors are politically difficult to accept and involuntary risk must be lower than voluntary risk.

The consensus seemed to be that the Ventilation Rate Procedure in Standard 62-1981 should be maintained. The Air Quality option could be modified. Permission for innovative procedures should be maintained. The standard should specify important pollutants and define maximum permissible levels. The standard should tell the designer how to use the information.

Specific recommendations and problems were as follows:

1. ASHRAE needs guidance on acceptable risks - is 10⁻³ acceptable? Morbidity risk rather than mortality risk should be used. Rationale for risk should not, however, be included in the standard. Simply staying at home should not increase personal risk.
2. There is a need to define risk in the home. Larger samples are needed.
3. Optimum environmental conditions for productivity need to be defined.
4. Indoor air pollutants need to be characterized on a broader scale.
5. Need methods to verify ventilation rates specified in Standard 62-1981.
6. Must determine ventilation effectiveness in buildings.
7. Need to evaluate effectiveness of air quality control options.
8. Need to improve human detection limits for formaldehyde.
9. Investigate health effects related to IAQ.
10. Improved instrumentation is needed both for research and for compliance tests.
11. Should occupational or environmental standards apply to the indoor environments?
12. How can we achieve implementation of, and compliance with the standard?

13. There is a need to model pollutant behavior in buildings. What is the relationship among comfort, energy, health, and productivity.
14. Need to define acceptability of body odor and tobacco smoke. How should the differences between visitors and adapted occupants be handled?
15. There is a need to coordinate with other organizations and trade unions.
16. How should sensitive groups (e.g. allergic or sick subjects) be considered?
17. Need to identify causes of sick buildings--identify causes and remedies.

Some Existing Indoor Air Quality Problems

J.A. Frazier

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE) has taken a progressive lead toward establishing the bases for defining and achieving "acceptable indoor air quality". The broad purpose of this workshop has been focused upon the ASHRAE Standard 62-1981, to determine whether there is a need and sufficient information available to revise the standard.

As a new member of the Society, it was of interest to read the bylaws. Since most of you do not regularly read them, there are two brief portions that appeared worth sharing at this meeting:

In the bylaws, the stated purpose of the Society is to advance the arts and sciences for the benefit of the general public, which implies that the health and comfort of occupants in buildings is of direct concern to the Society.

In its Code of Ethics, it is stated that the Society's efforts should be directed at all times to the enhancement of the public health, safety, and welfare.

This session of the meeting deals with problem definitions. The problems of achieving acceptable indoor air quality are viewed differently by some. As an example, this clip was taken from the April issue of Progressive Architecture: "The Conservation of Energy and Indoor Air Quality Need Not Be Conflicting Goals, Both The Causes and Cures of Indoor Pollution Are Diverse and Often Surprisingly Simple." Those present at the meeting will not view the indoor air quality problems as simplistic. In order to describe some of the problems and to characterize the information needed for decision making, consider a few examples.

There are three environments whereby exposure to the same pollutants can be encountered. The first is the work environment, defined by the Occupational Safety and Health Administration's standards for the quality of the air in the workplace; the second establishes standards for the ambient air under the Clean Air Act; and the third is the indoor environment broadly defined as the individual residences, recreation areas and public buildings. The ASHRAE has included in the Standard 62-1981 - Ventilation for Acceptable Indoor Air Quality concentrations for certain selected pollutants that are considered safe to the occupants. Consideration should be given to pollutants listed and the concentrations for them

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to determine whether new information would necessitate changing the concentration. Consideration should be given to the need for more comprehensive documentation of the data used to develop these standard concentrations. Other pollutants should be considered to determine whether they should be added to the list. Some of the pollutants for which concentrations have been established in the indoor environments are given in the following Table 1 (Table 4 taken from the Standard). Guidelines for concentrations of additional pollutants are given in other tables in the Standard.

The difficulties in choosing the "safe" concentration for indoor pollutants are greater than those in choosing the concentrations for the ambient air, e.g., ozone, carbon monoxide, and the other criteria pollutants. The problems indoors are of greater orders of magnitude because, and especially because of the greater range of susceptibilities of persons being exposed indoors. Also, data on some pollutants are not available for the aged, diseased or infirm, the very young, or the fetus.

Exposure and dose relationships are not synonymous terms. The actual dose received may differ from one person to another when both are exposed to the same concentration for the same time period. This is true because of differing rates of respiration, volumes of respired air, and rates of absorbance of pollutants by the cells of the body. The total dose must be considered in light of what is known about the toxicology of the pollutant. Here, again, it should be stressed that these data bases will commonly be found lacking in the information needed to assess the risks of the doses to some pollutants and especially to some of the susceptible subpopulation high risk groups shown in Table 2.

Three categories of threshold limit values for exposure have been established for the workplace environments: time-weighted-average (TLV-TWA), short-term-exposure limit (TLV-STEL), and ceiling (TLV-C). The ASHRAE Standard 62-1981 states that if any contaminant is not listed in Tables 1 or 2 of the Standard then guidance on acceptable exposure levels should be obtained by reference to the standards of the Occupational Safety and Health Administration. There is a question whether the OSHA standards for any given pollutant would be adequate for broad use indoors even if a reduction factor of 1/10 is used because the standards were established for the workplace and for working time periods. The workplace exposure periods are approximately 1/3 of the time of those exposure periods some persons can receive indoors. In addition, the standards for the workplace assume healthy adults capable of doing work. Conversely, the indoor environment has wider ranges of persons in age and states of health and susceptibilities to pollutants. These relationships must be carefully considered to determine that application of a 1/10 reduction factor will produce the margin presumed to be safe. The difficulties in changing a standard for critical pollutants once adopted into the building codes of the various states would be enormous.

The ASHRAE Standard 62-1981 needs to develop a repository of health effects data that is carefully reviewed by health experts to make the best judgments for choosing a concentration limit for a pollutant.

Welfare considerations such as temperature, humidity, and odors in the air are primary considerations in the ASHRAE Standard. The basic ventilation rates are established to deliver acceptable air quality. One of the first criteria for determining acceptable air quality was based on odors. Odors other than those caused by occupancy appear to cause significant problems. In the NRC report on odors, the results of a survey of the air pollution control districts in each of the United States showed that 50% of the pollution complaints were about community odors of outdoor origin that infiltrated indoors. One can speculate that these problems may diminish with the reduction of air infiltration in the energy-

Table 1
SELECTED GUIDELINES FOR AIR CONTAMINANTS OF INDOOR ORIGIN^a

Contaminant	Concentrations**	Exposure Time	Comments
Acetone—O*			
Ammonia—O			
Asbestos			Known human carcinogen, best available control technology.
Benzene—O			Known human carcinogen, best available control technology.
Carbon Dioxide	4.5 g/m ³	Continuous	See Appendix D
Chlordane—O	5 µg/m ³	Continuous	Reference 22
Chlorine			
Cresol—O			
Dichloromethane—O			
Formaldehyde—O	120 µg/m ³	Continuous	W. German and Dutch Guidelines
Hydrocarbons, Aliphatic—O			
Hydrocarbons, Aromatic—O			
Mercury			
Ozone—O	100 µg/m ³	Continuous	Reference 23
Phenol—O			
Radon	0.01 Working Level (WL)	Annual average	Reference 24 Paragraph 12.6 (background 0.002-0.004 WL).
Tetrachloroethylene—O			
Trichloroethane—O			
Turpentine—O			
Vinyl Chloride—O			Known human carcinogen, best available control technology.

* These materials marked "O" have odors at concentrations sometimes found in indoor air. The tabulated concentrations do not necessarily result in odorless conditions.

** Where concentrations are lacking refer to Section 6.1.1, Step No. 3. These substances are ones for which indoor exposure standards are not yet available.

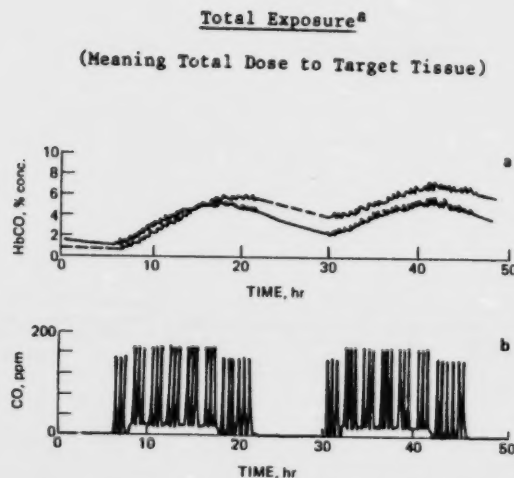
^a Taken from ASHRAE Standard 62-1981 - Ventilation for Acceptable Indoor Air Quality, p. 13. Atlanta, Georgia: The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1981.

Table 2

Identifying Factor for Some Types of High Risk Exposure Groups

- I. Developmental Factors
Immature enzyme detoxification system; immature immune system; deficiency in immune response due to aging; other aging factors; e.g., decline in renal function.
- II. Genetic Disorders
Red blood cell disorders--sickle cell and hemolytic anemias; glucose-6-phosphate dehydrogenase deficiency.
Serum disorders--cholinesterase variants; serum alpha-1 antitrypsin deficiency.
Homeostatic-regulatory disorders--cystinuria.
Immunological disorders--immunoglobulin A deficiency; hypersensitivity to chemicals.
- III. Dietary Deficiencies
Vitamin A, C, D, and E, and certain fats and proteins.
- IV. Other Enzyme Deficiency--Aryl Hydrocarbon Hydroxylase
- V. Diseases of Organs--Heart/Lung; Kidney; Liver
- VI. Behavioral Factors--Smoking, Drinking; Drug Habits; Eating Habits.

--Adapted from Boulos, 1978



efficient homes being built today. In energy-efficient homes, the reduced infiltration rates will carry less of the outdoor odorous air to the indoors. This may result in the occupants becoming more aware of odorants originating indoors, e.g., pets, occupancy odors, cooking, and especially tobacco smoke. Smoking causes special problems in ventilation requirements as noted in the range of increases in cfm required for any indoor areas where there is smoking. The ASHRAE standard shows increases of 2 to 6 or 8 times the cfm of air needed in indoor environments where there is smoking. Attention has been given to restrict smoking indoors in some localities because it does require increases in ventilation and because it is an easily-controlled source of pollution.

As an illustration, the smoking of tobacco contributes approximately 400 chemical pollutants into the indoor environment but let us look at direct smoking and use carbon monoxide from this source as an example. The additive dose of carbon monoxide from direct smoking is shown in Figure 1, taken from the NRC study on carbon monoxide. It shows there can be a gradual incremental increase in the carboxyhemoglobin dose to the target tissues resulting from smoking cigarettes, as shown in the lower half of the figure. Additional studies are needed to strengthen these data because the contribution of carbon monoxide and other hazardous chemicals in tobacco smoke to the body burden of the nonsmoker is poorly characterized.

The "Alert" presents another set of problems. The question is who received the complaint about an indoor pollution problem. The important issue is how to coordinate the follow-up investigation on the sources, concentrations of specific pollutants, what were the health effects in exposed persons, and who made the medical examinations. Unique problems arise in conducting these followups depending on the building types. For instance, in an individual residence, the homeowner may be unsure who to contact and may not know the air pollution control district or health department that can assist. In multi-apartment, commercially-leased residences, the building manager may not call upon the building engineer if the ventilation system appears to be operating improperly. Without proper and thorough investigations, ventilation problems cannot be adequately characterized, nor concentrations of pollutants measured, nor other relevant facts be collected during the episodes causing the problem. Formaldehyde pollution problems in residences were not adequately investigated in early episodes. Consequently, the complaints about health effects caused by formaldehyde were not correlated with exposures because measurements of formaldehyde concentrations often were not done until much later and frequently the expertise for making them was not available. Perhaps an equally important point is that commonly there were no attempts to determine whether other pollutants were also present that could cause the same symptoms or that could act in concert to heighten the magnitude of the symptoms experienced by those exposed.

What is the current technological capabilities for followup on indoor air pollution problems? In 1982, the Center for Disease Control sent a questionnaire to the State Health Departments in each of the 50 United States. The questionnaire sought information about the national indoor air pollution (NIAP) problems in each state. Responses were obtained from each of the 50 states. Some excerpts of the findings of this survey are given below to illustrate that there is a lack of technological capabilities for follow-up on indoor air pollution problems. Some readers may feel it is unfair to only report the problems in the survey results; however, this is the purpose here. It is recognized that some states do have the following technological capabilities in the NIAP.

- o Is there a specific NIAP program? 32 states said yes; 19 said no.
- o What NIAP field services or research activities are available? 11 states had none; 15 could evaluate exposures only; 11 could evaluate both exposures and health; 8 could evaluate exposures and conduct research on the health effects; 6 could provide advice, consultation or only make health evaluations.
- o Are there existing or proposed NIAP standards? 47 states said no.
- o Are there circumstances under which the state NIAP offers comprehensive medical-epidemiological evaluation of health complaints related to formaldehyde? 39 states said no.
- o When does the NIAP consultant refer formaldehyde inquiries to a physician or other health professional? 30 states said only when there were persistent symptoms.
- o What types of collecting device(s) and analytical method(s) are used? 22 states offered none; 20 collected area samples only.
- o What types of air samples are collected under what conditions? 22 states offered none; 22 states took area samples only under "unusual" conditions.
- o What environmental data are routinely collected at the time of air sampling? 22 states offered none; 15 states did not specify the data; 14 states collected temperature, humidity, ventilation, occupancy/use characteristics and some source data.

The bias inherent in selectively picking only problem areas in these results of the survey is acknowledged. This has been done to show some of the needs for technology development if follow-ups are to be made on indoor air pollution "alerts/complaints".

A documentation file of health effects data on each pollutant and existing problems showing the relationships of ventilation and pollution to health effects is needed to support the ASHRAE Standards for Indoor Air Quality that establishes a concentration for any pollutant indoors in its revision of the 62-1981 Standard.

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Formaldehyde Release from Building Materials

B. Meyer

ABSTRACT

During the last fifteen years Urea-Formaldehyde (UF) bonded particleboard, medium density fiberboard and plywood have replaced whole wood as a construction material for flooring, wall paneling cabinet work and furniture. At the same time, Urea Formaldehyde Foam Insulation (UFFI) was widely promoted as a large-scale retrofitting material for wall insulation. This accumulation of UF-bonded products revealed the need for formaldehyde release material standards for all types of UF-products. Results of our tests show that the rapid development of the last five years has produced material test methods that are adequate for classifying materials, and UF-resins as well as UF-bonded wood products that are capable of meeting ASHRAE 62-1981 or similar standards at the current product use ratio. Thus, as soon as appropriate formaldehyde material standards are accepted and implemented, the only complaints left will be those due to defective materials.

INTRODUCTION

While normal outdoor formaldehyde levels are between 5 and 50 ppb, depending on location,¹ indoor air levels are often significantly higher. Formaldehyde vapor can arise from tobacco smoke, oil and gas fired kitchen and heating stoves, and even textiles, but the most significant potential sources are Urea-Formaldehyde (UF) resin containing products² such as formaldehyde based foam insulation (UFFI), hardwood paneling, plywood, particleboard and medium density fiberboard (MDF) that are used as structural materials, wall paneling, cabinet work and for furniture. During the last two decades UF-bonded wood products have replaced whole wood to such an extent that, today, many buildings and especially mobile homes, contain more than 1 m² of these products per 1 m³ of indoor air. Under such conditions, even traces of residual formaldehyde in the product may cause measurable off-gasing into indoor air, especially when the ventilation rate is reduced to preserve heating and air conditioning energy. Thus, formaldehyde, an industrial chemical that has filled the air in hospitals and medical offices as a disinfectant for almost a century, suddenly found an unexpected potential entry into offices and homes.

CONSUMER COMPLAINTS

Since formaldehyde works as a disinfectant by pickling proteins and DNA, it is not surprising that it can cause acute health problems³ and that its odor is unpleasant and irritating. Likewise, the fact that UF-bonded products can release residual unreacted formaldehyde has been well known since the invention of particleboard by Fahrni in 1944. However, consumer complaints about high formaldehyde indoor air levels surfaced only after these products gained so much popularity that they replaced whole wood in almost every building for almost every application. The first industry conference dealing with formaldehyde reduction was published in Leipzig, Germany, in 1964.⁴ The first widely publicized complaint was probably that of public school teachers in Karlsruhe, Germany, who abandoned a new classroom building in early autumn of 1973 because of irritating odor. The problem arose because ventilation was insufficient⁵ and had been turned off for several weeks during vacation, during the hottest summer of the century, in a new building containing large quantities of freshly manufactured particleboard. Similar

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problems have been reported in Scandinavia⁶, Czechoslovakia and Russia². In Canada and the U.S. persistent problems have been reported in temporary or portable school structures that contain exotic hardwood paneling. In most of these cases, the problem is aggravated by poor ventilation design that is evident from noticeable body odors in the class rooms. Often, one also finds visible moisture stains from condensation.

Probably, the most wide-spread complaints concern mobile homes, buildings that are used as residences as well as offices. These are designed to provide the most economic housing possible. Thus, they contain a combination of design factors that rely upon upmost quality control in all of their components. During the energy crisis of the 1970s, when mobile home envelopes were tightened to reduce infiltration, air exchange rates dropped to a level where the potential for formaldehyde release from three different types of materials (exotic hardwood paneling, particle board flooring and pressed wood cabinet work and furniture) resulted in a greatly increased combined risk. Thus, for several years, formaldehyde levels in new mobile homes were often above the odor threshold, and sometime reached occupational safety standard limits.⁷ Such high levels cause distress to occupants, and may cause acute health problems.³ Fortunately, recent advances in UF resin formulation and quality control have made any elevated formaldehyde air levels unnecessary, and, hopefully, a thing of the past.

A separate and particularly serious problem arose in the middle 1970s in North America from the sudden demand for an efficient insulation material for retro-fitting residential building envelopes. Formaldehyde based insulation (UFFI) seemed to fit the bill, and was widely promoted by private and public agencies, because the foam can be formed and shaped on-site, by injecting reactive, wet fluid into wall cavities. UFFI has been used for several decades in Europe⁸ with few complaints, because material quality and installation quality has been carefully controlled. UFFI is economical, has an outstanding insulation rating and is so fire resistant that it has been used to protect steel beams in tall office structures. Furthermore, carefully formulated UFFI is environmentally compatible and can be used as a fertilizer and even as a surgical wound powder.² However, unfortunately, in North America there have been persistent problems that became increasingly evident from the inception of the sudden large-scale introduction. These complaints are due to different wall construction materials and design, different application techniques, sometimes careless installation, sometimes lacking technical skills and understanding, and the lack of any material standards. Even though the number of complaints has been comparatively small, faulty UFFI can cause highly expensive repair problems or even permanent damage to the structure, and thus constitutes a disproportionate and unnecessary risk. Extensive research and development is still necessary before UFFI can reliably live up to its potential as a most economical and efficient large-scale home insulation material in North America.

FORMALDEHYDE CHEMISTRY AND VAPOR PRESSURE

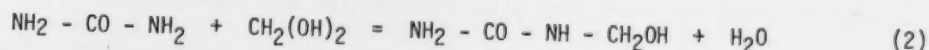
The study of formaldehyde release is difficult because of the unusual chemical properties of this molecule. Even though it is a permanent gas, formaldehyde can also exist as a solid polymer and, furthermore, it can reversibly react with moisture to form methylene glycol, a molecule that can form stable aqueous solutions from which formaldehyde gas can re-emerge when the moisture vaporizes:



Thus, formaldehyde can accumulate in congealed form in wall, ceiling or floor condensation, along air conditioner ducts or on kitchen vents. This situation is further complicated by the equilibrium moisture content of the wood that surrounds the cured UF resin, and that covers indoor surfaces. The wood moisture content varies from about 6 wt% at 30 %RH to 27 wt% at 98 %RH.⁶ This high moisture adaption capacity is one reason why wood structures are so comfortable in all types of climates, but the transfer between air and wood is slow, and, thus, the process of moisture equilibrium is a continuous adjustment process that is overlapped by diurnal and seasonal humidity cycles. As the moisture content of wood changes, the concentration of the formaldehyde solution within the wood changes, the equilibrium vapor pressure of formaldehyde above the wood surface changes, and thus the observed indoor air concentration changes. The calculated formaldehyde equilibrium pressure is shown in figure 1. Typical formaldehyde air levels observed in a new and unoccupied mobile home are shown in figure 2. In a real-life setting the situation is yet further complicated by the metabolism of occupants and by their activities.¹

FORMALDEHYDE SOURCES

UF-bonded particleboard and medium density fiberboard (MDF) are made by hot pressing wood chips that have been resinated with 5 - 10 wt% of UF resin. The chips are formed into mats and pressed at 150 - 190°C for a period of about 10 sec per mm thickness of the finished product. During the press period hot steam from the moist wood particles transfers heat, formaldehyde and other volatiles from the surface of the mat to the core of the board where unreacted resin components accumulate. Thus, the formaldehyde concentration in the core of boards is about twice that of the surface. In the past, when UF resins with high excess free formaldehyde were employed, the content of residual latent formaldehyde was usually between 50 to 100 x 10⁻⁵ wt%. Progress of the last few years, including the use of low F:U ratio resins and the use of scavengers, has made it possible to reduce latent formaldehyde content by a full factor of ten without abandoning conventional UF resin art. 9-11. Thus, a modern 16 mm particleboard contains now only about 1 gram of latent formaldehyde per m². The release of formaldehyde from the board surface into indoor air is diffusion controlled unless the paneling is part of a faulty installation in a building envelope that serves as a source of air infiltration. In any case, the formaldehyde release gradually decreases over time, as the latent free formaldehyde is removed. This time dependence is shown in figure 3. It is not exponential as one would expect for a first order reaction, because formaldehyde interacts with wood moisture, wood cellulose chemical functions and lignin, and because formaldehyde release triggers a fairly complex chemical equilibrium system in the residual resin. Schematically, the formaldehyde equilibrium can be represented by the first reaction step with urea yielding methylol. The reverse of this reaction is the hydrolysis of resin liberating formaldehyde and urea:



The corresponding equilibrium constant is:

$$\frac{[\text{NH}_2 - \text{CO} - \text{NH} - \text{CH}_2\text{OH}][\text{H}_2\text{O}]}{[\text{NH}_2 - \text{CO} - \text{NH}_2][\text{CH}_2(\text{OH})_2]} = k = 2 \times 10^{-2} \text{ moles/liter} \quad (3)$$

Thus, moisture greatly enhances formaldehyde release. However, formaldehyde release produces residual urea, a non-volatile solid that stays within the wood. This urea acts to shift the equilibrium backwards, i.e. it acts as a scavenger. Modern resins contain excess urea that enhances this effect.¹¹ Formaldehyde release rates of commercial boards currently vary from 10 mg/m² hr to less than 0.5 mg/m² hr for UF bonded boards 9-15 depending on the resin quality used, the quality control in the wood products manufacturing process and other factors. Introduction of new technology has been slow because it is an interdisciplinary process involving a chain of industries ranging from the base chemical producers to resin manufacturers to forest product manufacturers to home builders and, finally, to the consumer. Each segment in this chain has only limited control over its next nearest supplier. In Japan¹⁶ and Europe¹⁷ the process has been significantly accelerated by the early development of material standards,¹⁶⁻¹⁸ and classification of products.¹⁸

UF-bonded plywood contains 2.5 wt% resin, all concentrated in the glue line. This type of product is only used for interior applications. Outdoor plywood is bonded with phenolic resins that have only negligible formaldehyde release.¹ In contrast, formaldehyde emission from indoor wall paneling is difficult to control, because in some finishing processes solid polymeric formaldehyde is added as a catalyst for curing. Efforts are now under way to solve these problems. European indoor plywood is often produced with melamine resins that have greatly reduced emission.

Urea-formaldehyde foam insulation (UFFI) has already been mentioned. It is made by foaming UF resins with air in the presence of an acid catalyst and a surfactant in a specially designed air gun that contains a mixing bed.² Formaldehyde release of a well made UFFI is similar to that of particleboard or MDF. Poorly mixed UFFI, containing either excess of hardener or excess of resin, is capable of releasing formaldehyde over its entire lifetime. In extreme cases the material has been found to remain liquid in the building walls, or in the other extreme it may convert to a friable powder. Well prepared and well placed UFFI in a properly designed and ventilated building envelope is hard to excel as a thermal insulator; poor UFFI can ruin a building by impregnating it with unreacted formaldehyde.

FORMALDEHYDE MEASUREMENT AND PRODUCT CHARACTERIZATION

Several measurement methods for predicting indoor formaldehyde levels are now available. For a reliable product performance prediction it is necessary to know (a) the total latent formaldehyde content, and (b) the formaldehyde release rate under standardized conditions. The best method for determining the latent formaldehyde content is still the European Perforator Standard test¹⁷, even though this test is no longer sensitive enough to differentiate among the best of the current commercial products. Several different methods are currently in use for measuring formaldehyde release rates. The oldest standard method is the Japanese Industrial Standard JIS-A5908-1974, using a 10 liter desiccator.¹⁶ The North American desiccator test²¹, FTM-1, is a less sensitive version using the same principle: Eight product samples, 2.75 x 5 inches are enclosed in a 10 liter desiccator for 2 hrs. Formaldehyde is collected in 20 ml water that is kept in a 10 cm diameter dish inside the desiccator. The formaldehyde release rate is expressed in mg/l collecting solution, as determined with standard colorimetric methods. In the current version the sample edges are sealed with wax to exclude emission from edges. This test can also be run with dry collector materials, such as sulfite filters or zeolites.²² In Europe, the most popular test is probably the WKI-test²³. It is similar to the U.S. textile test AATCC method 112-1978,²⁴ and suffers from the same problems as all accelerated tests in that it over-emphasizes formaldehyde release from those chemical functions that are temperature and moisture sensitive. The most reliable, but also the most impractical and expensive test, is full-scale testing of boards in large air chambers²⁵⁻²⁷. Currently some six different large test chamber designs are in use. Such tests reveal that formaldehyde release does not only depend on temperature but also on the ventilation rate.²⁸ If different products are combined, the low emitting material may well act as a scavenger for the high emitters⁹, but the combination effect is not easily predicted. In contrast, the temperature and humidity dependence of formaldehyde emission from pressed wood products can now be reliably predicted over a large range by the equation:

$$C = C_0 [1 + Ah] \exp -9799 \left(\frac{1}{T} - \frac{1}{T_0} \right) \quad (4)$$

where C is the observed concentration, C_0 the standard concentration at 20°C and 50 %RH, A is a humidity coefficient with a value of 0.0175 and h the difference between the standard and the observed relative humidity.²⁹ The temperature effect is shown in figure 4. The emission increases by more than a factor of 2 at 90°F, and drops to about 40% at 60°F, with an average temperature coefficient of about 6 %/°F or 3.5 %/°C. A 10 % humidity change causes a 18 % change in emission. Since the emission is highly sensitive to both temperature and humidity, the measurement conditions must be carefully monitored. In fact, for standard tests, the samples must be conditioned for five days before they reach full equilibrium. This fact is not always recognized by those who study indoor air formaldehyde levels caused by pressed wood products. Furthermore, it is not always easy to have adequate knowledge of the temperature and humidity of wood products present in the indoor environment, because the indoor air temperature and humidity is not necessarily the same as that of materials in the wall envelope. In fact, in most structures, there are significant temperature and humidity gradients through the wall and floors. Furthermore, these gradients differ between parts of the building that are exposed to the sun and other parts that may be exposed to cold winds. Finally, these gradients may change with diurnal and seasonal cycles. This situation explains the great variation observed in field tests, such as those shown in figure 2. As far as laboratory conditions are concerned, the correlation between the desiccator and the perforator tests are well established.^{9,26-28} The calculated relationship between the 2 hr U.S. desiccator tests and large air chamber values is shown in figure 5. This figure shows values for six currently available commercial resins. Resin G, a commercial UF resin, is capable of maintaining air levels below 0.1 ppm within five days of manufacture. However, as indicated in figure 2, actual field levels will depend on ventilation, occupancy, insolation, heating or cooling and many other factors.

FORMALDEHYDE GUIDELINES AND STANDARDS

Air Standards. The current OSHA eight hour time weighted work safety and health standard is still 3 mg/m³. This is about three times higher than occupational standards in most other industrial countries where values are mostly around 1 ppm. Calculated for a thirty hour work week, the latter value leads to a weekly formaldehyde dose of 30 ppm hrs. Assuming a breathing rate of 30 l/min, this adds up to more than 50 mg formaldehyde per week. For a home maker who spends 154 hrs per week at home¹, this occupational dose limit is reached if indoor air levels average 0.19 ppm. However, this does not allow for any of the recovery time that is provided for under industrial standard conditions. Thus, an average home exposure level of 0.19 ppm corresponds to an annual dose of about 2 grams of formaldehyde. Therefore, military standards and European indoor standards all aim at a level of about 0.1 ppm. This is the same level as

that adapted in ASHRAE 62-1981. As stated above, this level has been achieved in several countries since 1979 with UF-bonded wood products, at an extra cost of about 20%. In fact, all European particleboard manufacturers have now available boards that can satisfy this level. In the US, standard production board that can meet this same 0.1 ppm air level has become available since summer 1983, on a limited basis, at no extra cost.

Material Standards and Product Classification. The key to the introduction of low emitting particleboard has been the development of voluntary material testing standards.^{2,9,16-18} The way was led by the perforator test, invented by Verbestel in 1964, developed by FESYP, the European Association of Particleboard Manufacturer Associations, that made it into an international voluntary standard that has now become a formal European Standard CEN/TC EN 120-1982. Parallel with this development, the carefully designed Japanese Standard JIS A-5908 was introduced, as explained above.² Currently, European boards are classified according to the German system. Class E-1 applies to boards with perforator values of 10mg/100g or less. This corresponds to an US desiccator value of about 1 mg/l, and translates into an air chamber value of about 0.1 ppm. Boards with a perforator value of 30 mg/100g, a level that was thought to be the best possible with UF resins in 1976, are now no longer admitted to the European market.

In the North American market similar developments commenced around 1979. Low formaldehyde emission has become a competitive sales issue since summer 1981 when several large companies publicized the introduction of low odor formaldehyde technology boards with air chamber values of about 0.2 ppm. In spring of 1983 the National Particleboard Association and the Hardwood Plywood Manufacturers Association jointly published their Tentative Test Methods FTM-1 and FTM-2, using the 2 hr desiccator and the large air chamber, respectively. These tests are similar to those published by the U.S. Department of Housing and Urban Development as part of the proposed revision of the Manufactured Home Construction and Safety Standards.³⁰ No final agreement has yet been reached about the formaldehyde levels that are to be considered acceptable by HUD, but the proposed methods are capable of measuring material properties in the range of 0.1 ppm that is necessary to meet most international standards and ASHRAE 62-1981.

CONCLUSIONS

Material tests of currently available UF-bonded wood products show that formaldehyde emission levels vary over a factor of ten, as shown in figure 5. ^{10,14} Several commercial products are capable of meeting the German classification E-1 that corresponds to air chamber values of about 0.1 ppm. The current rapid technical development indicates that commercial materials are now capable of meeting ASHRAE 62-1981 under normal use conditions and loading. In fact, our tests indicate that formaldehyde emission from current state-of-the-art boards may well reach ambient indoor air formaldehyde levels. Thus, problems with formaldehyde release from pressed wood products will soon be a thing of the past, except for problems caused by defective materials or improper use. As far as UFFI insulation foam is concerned, the forecast is more difficult. However, it certainly will take many years before large scale use of this promising material will reach the level of reliability now achievable with UF-bonded wood products.

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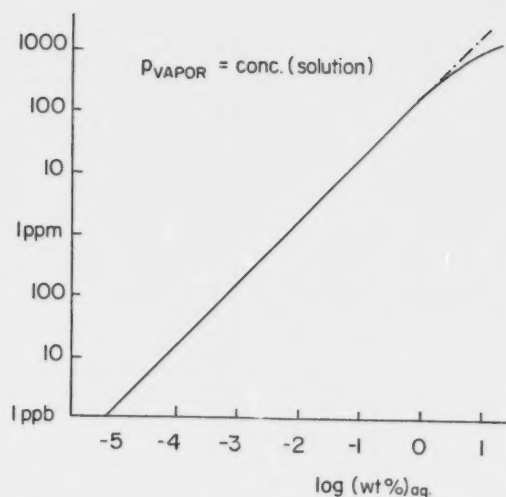


Figure 1. Equilibrium vapor pressure of formaldehyde as a function of concentration at 20°C²

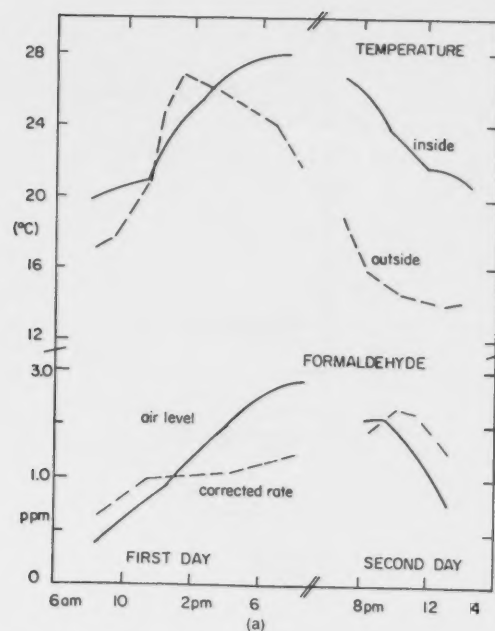


Figure 2. Indoor formaldehyde air levels in an unoccupied mobile home as a function of daytime¹

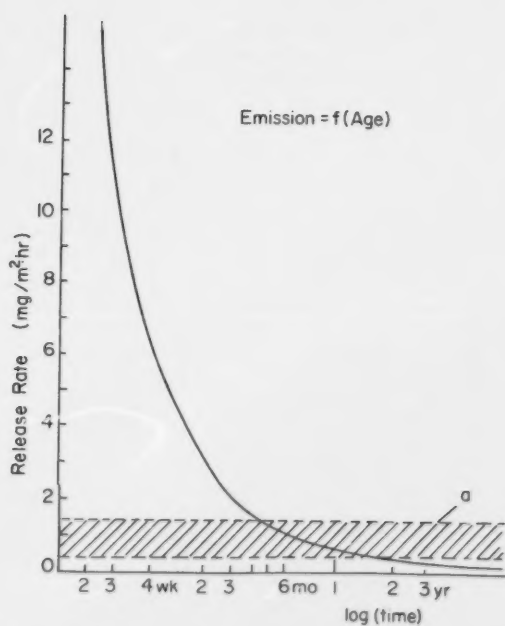


Figure 3. Formaldehyde emission from medium density fiberboard as a function of age

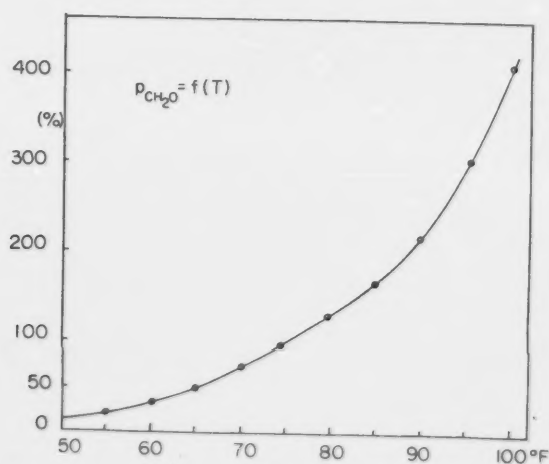


Figure 4. Temperature dependence of formaldehyde release from particleboard as calculated from Berge equation³

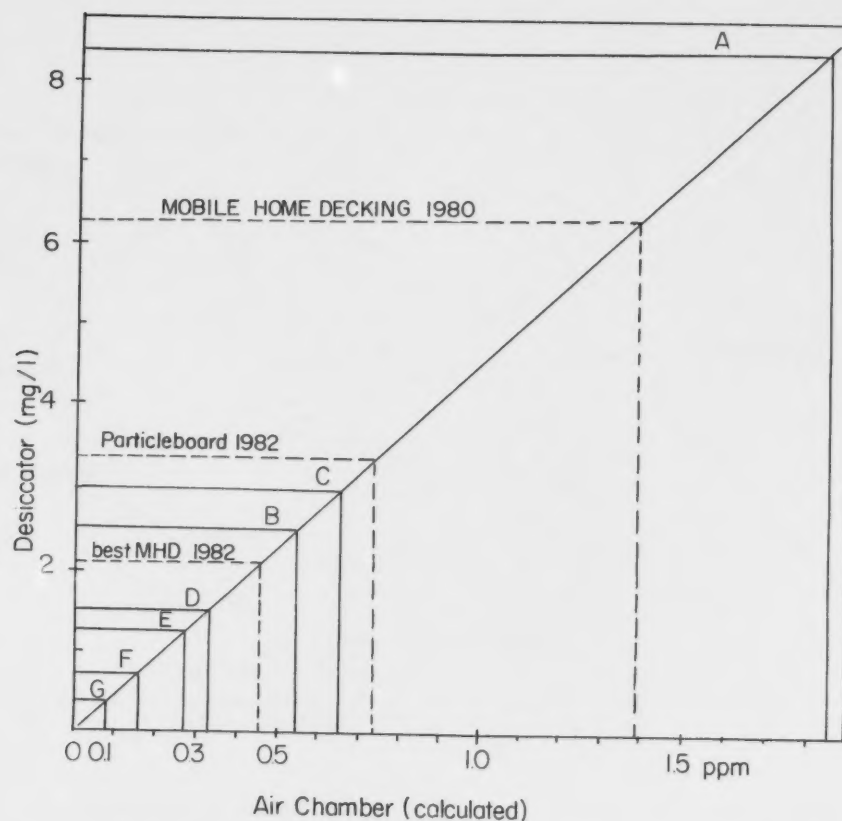


Figure 5. Correlation between observed U.S. 2 hr desiccator value and calculated air chamber value for medium density fiberboard fabricated in a commercial pilot plant with seven UF-resin adhesives that were commercially available in Spring 1983. The figure also shows progress made in the average formaldehyde emission from mobile home decking during the period from 1980 to 1982.

Formaldehyde Emissions from Combustion Sources and Solid Formaldehyde Resin Containing Products: Potential Impact on Indoor Formaldehyde Concentrations and Possible Corrective Measures

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ABSTRACT

The formaldehyde (CH_2O) emission rates of combustion sources and solid CH_2O resin-containing products commonly found in domestic environments are surveyed. The potential contribution of these sources to indoor CH_2O concentrations are estimated using simple steady-state, indoor pollutant concentration models. The strongest contributors to indoor CH_2O are pressed-wood products and foam insulation containing urea formaldehyde resins. Combustion sources and phenol-formaldehyde resin-bonded products are generally weak emitters. Potential corrective measures to reduce indoor CH_2O concentrations are reviewed. Ammonia fumigation, permeation barriers on non-decorative surfaces, and increased ventilation may be useful techniques to reduce the contribution of strong solid emission sources until the CH_2O emissions are reduced to more acceptable levels through normal product aging.

INTRODUCTION

Non-occupational indoor environments can contain a variety of CH_2O emitters including both combustion sources and solid CH_2O -resin containing products (Figure 1). Common combustion sources include gas burners and ovens, kerosene heaters, and cigarettes. Consumer and construction products incorporating CH_2O resins include urea-formaldehyde foam insulation (UFFI), pressed-wood products, fibrous glass insulation, ceiling panels, and textiles. The potential contribution of each source to indoor CH_2O concentrations depends on the CH_2O emission characteristics of the product, product use parameters, and the ventilation characteristics of the indoor environment. For combustion appliances, wide variation in the CH_2O emission rates can be expected on the basis of product design, tuning, and duty cycle (Girman, Geisling, et al., 1983). The efficiency of the combustion process and thus the CH_2O generation rate may also be a function of a warm-up cycle or oxygen concentration in the indoor atmosphere (Girman, Allen, et al., 1983). The CH_2O emission from CH_2O resin-containing products is generally a function of the type and amount of resin it contains, environmental parameters such as temperature, relative humidity (RH), and room CH_2O concentration, and the age of the material. Product use parameters include the loading of the material [i.e., surface area (m^2)/air volume (m^3)]* and the presence of intervening permeation barriers, such as resilient flooring or plastic vapor barriers, between the CH_2O emitter and the indoor atmosphere. In indoor environments that depend on natural ventilation for pollutant removal, the air infiltration rate for the dwelling, distribution of emission sources, and intercompartment mixing efficiencies are all important parameters. Formaldehyde concentrations outside the home are generally very low (i.e., <0.01 ppm) and thus have a minimal contribution to indoor concentrations (Calvert et al., 1981).

*A units and conversions listing is given in Appendix I.

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Corrective measures for indoor environments with unacceptable CH₂O concentrations generally fall into two categories: product specific actions and general procedures that contribution on several emission sources throughout the dwelling. When a product has been identified as a primary contributor to indoor CH₂O concentrations, it can be removed, replaced with a lower emitting product, or covered (i.e., sealed) with a permeation barrier. Dwelling treatments, such as ammonia fumigation or increased ventilation using exhaust fans or heat exchangers, reduce the contribution of several CH₂O emission sources.

To select an appropriate action to reduce indoor CH₂O concentrations in planned or existent dwellings, the potential contribution of the primary emission sources within the dwelling should be assessed. The CH₂O emission rates of a variety of CH₂O resin containing products and combustion sources have been surveyed. These emission rate data will be used with simple steady-state models for indoor pollutant concentration to determine the potential contribution of each source to indoor CH₂O concentrations. The models will also provide a tool to evaluate potential corrective measures such as source removal, permeation barriers, and increased ventilation. The steady-state models cannot address the contribution of time-dependent changes in source, environmental, or ventilation parameters. The effects of changes in temperature and humidity on the steady-state emissions from solid CH₂O resin-containing products will also not be considered in these models.

FORMALDEHYDE EMISSION RATES FROM COMMON COMBUSTION AND FORMALDEHYDE RESIN-CONTAINING PRODUCTS

Most CH₂O emission sources can be conveniently divided into three categories:

- [1] combustion sources,
- [2] CH₂O resin containing products with direct exposure in the indoor atmosphere, and
- [3] CH₂O resin containing products separated from the indoor atmosphere by an intervening permeation barrier.

Combustion sources that are commonly used throughout the U.S. include gas stoves, kerosene heaters, and cigarettes. Formaldehyde emissions from all three categories of sources have been measured in room size environmental chambers under approximate consumer use conditions. These experimental results (and references) are summarized in Table 1. Average duty cycles are also reported for each combustion source, which are considered to be crude estimates of highly variable consumer use patterns. The average duty cycle for a single gas burner and gas oven were calculated for a typical U.S. family of four with average income accounting for contemporary pilotless burner designs (Macriss, 1984). The average gas-energy consumption for cooking, 19,000 Btu/day, was divided into two roughly equal portions, 9,000 Btu/day for gas burners and 10,000 Btu/day for a gas oven (Macriss, 1984). For a gas burner, an average energy consumption rate of 9,000 Btu/hr yielded an approximate duty cycle of 1.0 h/day. For a gas oven, an average energy consumption rate of 15,000 Btu/h yielded a duty cycle of 0.7 h/day. The average duty cycle for kerosene heaters (i.e., 8 h/day) during the heating season has been estimated by the U.S. Consumer Product Safety Commission (White et al., 1983). The average cigarette consumption rate was estimated from U.S. Department of Agriculture statistics (Horn, 1978). In 1978, 53 million U.S. smokers consumed 615 billion cigarettes. Assuming a single smoker per family of four, this corresponds to a cigarette consumption rate of 32 cigarettes per smoker per day. A cigarette consumption rate of 10/day in the modeled compartment is assumed, reflecting the potential for smoking in several different locations both inside and outside of the compartment.

For each combustion source, the average CH₂O emission rate over a 24 h period has been calculated (Table 1). This data is used in subsequent modeling to predict the potential steady-state contribution of each source on indoor CH₂O concentrations. The average emission rates for all three categories of combustion sources are fairly similar, constituting a range of about 0.2 to 1.3 mg/h.

There are many varieties of CH₂O resin containing products with direct exposure in the indoor environment (Table 2). The significant emitters are typically pressed-wood products incorporating urea-formaldehyde resins. Textiles, carpeting, ceiling tiles, and resilient flooring are generally weak emitters. Urea-formaldehyde foam insulation is a potentially strong CH₂O emitter that is frequently separated from the indoor environment by gypsum board in exterior wall construction. However, in this report UFFI is treated analogously to emitters with direct exposure because the CH₂O emission rate data were taken from simulated wall panels with an interior surface of painted gypsum wallboard (Hawthorne et al., 1981). These panels contained no plastic vapor barrier between the UFFI and the gypsum board wall.

The remaining CH₂O resin containing products with indirect exposure in the indoor environment are listed in Table 3. With the exception of particleboard underlayment, all are weak CH₂O emitters. Softwood plywood subflooring is typically among the weakest pressed-wood emitters because it is fabricated with phenol-formaldehyde resins (Emery, 1984). In contrast, urea-formaldehyde resins are used in most particleboard (except waferboard and oriented strand board), hardwood plywood paneling, and medium density fiberboard products (Emery, 1984).

The product conditioning and CH₂O emission rate measurement techniques used to characterize the CH₂O emission sources listed in Tables 2 and 3 are varied. The CH₂O emission rate data for textiles and carpeting have been reported by Pickrell et al., (1983) for purposes of product ranking. Product conditioning and testing were performed at 22°C and 100% relative humidity in sealed desiccators. The quantitative relationship between the CH₂O emission rate measurements under these test conditions and environmental chamber tests under simulated real-world conditions (e.g., 23°C, 50% RH, <0.2 ppm CH₂O) was not determined. However, the CH₂O emission rates of the textile and carpet products were sufficiently low that such intermethod correlations are presumably unimportant.

The data for pressed-wood products, fibrous glass insulation, carpet cushion, ceiling tiles, and resilient tile flooring were taken using the Oak Ridge National Laboratory (ORNL) developed formaldehyde surface emission monitor (FSEM) and environmental chamber test methods. Product conditioning was at -23°C and 50% RH. The FSEM is a passive, non-destructive flux monitor that uses 13X molecular sieve to collect emitted CH₂O and maintain low CH₂O concentrations (typical of indoor environments) near the surface of the emitter. A strong, approximately 1-to-1 correlation between CH₂O emission rate data taken with the FSEM and small scale environmental chamber tests (at 23°C, 50% RH, and 0.1 ppm CH₂O) has been measured for a variety of pressed-wood products and UFFI encased in simulated wall panels (Matthews, Hawthorne et al., 1984). A similar, but more qualitative, intermethod correlation has been observed for measurements of fibrous glass insulation and ceiling tiles (Matthews, Westley, 1983).

INDOOR FORMALDEHYDE CONCENTRATION MODEL

In this report, a simple steady-state model for indoor pollutant concentration is used to estimate the potential contribution of a variety of CH₂O emission sources to the CH₂O concentration in a single compartment. The indoor air quality model is based on the pollutant mass balance equation of Wadden and Scheff (1982). Separate emission models are also developed for: (1) combustion sources, (2) CH₂O resin-containing products with direct exposure in the indoor compartment, and (3) solid emission sources separated from the indoor compartment by intervening permeation barriers. The emitter models are incorporated into the pollutant concentration model to account for any CH₂O concentration dependence of the emitters. All modeling is restricted to standard temperature and relative humidity conditions (i.e., 23°C, 50% RH). The steady-state modeling will not consider the contribution of short-term changes in emission sources, environmental or ventilation parameters, and the resulting time-dependent CH₂O concentration behavior. Assumptions for each step in the model development are identified.

Steady-State Formaldehyde Concentration Model for a Single Compartment

At steady-state, the CH₂O concentration in a single compartment may be expressed as:

$$[\text{CH}_2\text{O}]_{\text{SS}} = [\text{CH}_2\text{O}]_0 + \text{CH}_2\text{OER} / (C \cdot \text{ACH} \cdot \text{VOL}) \quad (1)$$

where

$[\text{CH}_2\text{O}]_{\text{SS}}$ = steady-state CH₂O concentration inside the compartment (mg/m³),

$[\text{CH}_2\text{O}]_0$ = steady-state CH₂O concentration outside of the compartment (mg/m³),

CH_2OER = CH₂O emission rate of CH₂O sources inside the compartment under existing environmental conditions (mg/h),

C = fraction of air coming into the compartment that completely mixes within the compartment volume (where the remaining fraction of air, 1-C, does not mix within the compartment volume),

ACH = volumetric flow rate of air in and out of the compartment in units of compartment volume per hour (h^{-1}),

VOL = the volume of the compartment (m^3).

The simplifying assumptions are:

1. a steady-state condition,
2. all parameters in equation 1 are constant,
3. uniform mixing exists resulting in no CH_2O concentration gradients in the atmosphere inside the compartment,
4. no mechanical or natural air filtration systems exist, and
5. there are no permanent losses of CH_2O due to sinks.

In this treatment, water-bearing sorbent materials (i.e., sinks), such as gypsum board, are assumed to be a buffer to the attainment of a steady-state CH_2O concentration but not a permanent CH_2O loss mechanism. Consistent with this assumption, gypsum board has been shown to act as both a CH_2O sink and secondary emitter, dependent on the CH_2O vapor concentration surrounding the medium (Matthews, Hawthorne et al., 1984).

Noting that $C \cdot \text{ACH}$ is the effective pollutant exchange rate [$\text{PEX}(\text{h}^{-1})$] for the compartment,

$$[\text{CH}_2\text{O}]_{\text{SS}} = [\text{CH}_2\text{O}]_0 + \text{CH}_2\text{OER} / (\text{PEX} \cdot \text{VOL}) \quad (2)$$

For area dependent sources,

$$[\text{CH}_2\text{O}]_{\text{SS}} = [\text{CH}_2\text{O}]_0 + \text{CH}_2\text{OER}' \cdot \text{Area} / (\text{PEX} \cdot \text{VOL}) \quad (3)$$

where

$\text{CH}_2\text{OER}'$ = CH_2O emission rate of the solid, CH_2O resin-containing products ($\text{mg}/\text{m}^2\text{h}$) under existing environmental conditions, and

Area = area of the solid emission sources (m^2).

Source Emission Models for Combustion and Solid Emission Sources

The CH_2OER of combustion sources at steady-state is assumed to be a constant, determined from the mean emission levels measured in laboratory chamber studies averaged over a 24-h period using estimated duty cycles. The model does not account for potential short term escalations in indoor CH_2O concentrations due to intermittent use of combustion sources. In addition, the model does not account for the effects of any environmental, tuning, or warm-up parameters on the CH_2OER of combustion sources.

For solid emission sources with direct exposure, a negative linear dependence of $\text{CH}_2\text{OER}'$ on CH_2O concentration is assumed. This simple model is consistent with the application of Ficks Law to the bulk-vapor interphase at the surface of a solid emission source (Crank, 1979).

$$\text{CH}_2\text{OER}' = m([\text{CH}_2\text{O}]_B - [\text{CH}_2\text{O}]_V) \quad (4)$$

where

m = mass transport coefficient for the CH_2O emitter (m/h),

$[\text{CH}_2\text{O}]_B$ = CH_2O concentration in the bulk phase (mg/m^3), and

$[\text{CH}_2\text{O}]_V$ = CH_2O concentration in the adjoining vapor phase (mg/m^3).

Assuming that $[\text{CH}_2\text{O}]_B$ and m are insensitive to changes in $[\text{CH}_2\text{O}]_V$,

$$\text{CH}_2\text{OER}' \approx -m[\text{CH}_2\text{O}]_V + b \quad (5)$$

where

b = a constant, the $\text{CH}_2\text{OER}'$ ($\text{mg}/\text{m}^2\text{h}$) at zero CH_2O concentration in the air.

An approximately negative linear dependence of the $\text{CH}_2\text{OER}'$ on the CH_2O vapor concentration has been experimentally observed for a variety of pressed-wood products, UFFI, and fibrous glass insulation. A limiting condition is also applied to equation 5 that is consistent with assumption #4 for equation 1. At steady-state, the $\text{CH}_2\text{OER}'$ of all sources must be greater than or equal to zero. The product age dependence of the $\text{CH}_2\text{OER}'$ is not considered.

For solid CH_2O emission sources covered by permeation barriers, two linear equations are used to describe the $\text{CH}_2\text{OER}'$ of the source-permeation barrier combination. Fick's Law is used to describe CH_2O transport across the permeation barrier.

$$\text{CH}_2\text{OER}' = K([\text{CH}_2\text{O}]_{\text{BB}} - [\text{CH}_2\text{O}]_{\text{SS}}) \quad (6)$$

where

K = mass transport coefficient for the permeation barrier (m/h),

$[\text{CH}_2\text{O}]_{\text{BB}}$ = CH_2O concentration below the barrier (mg/m^3), and

$[\text{CH}_2\text{O}]_{\text{SS}}$ = CH_2O concentration above the permeation barrier (mg/m^3).

It is assumed that no CH_2O concentration gradients exist below or above the permeation barrier. This simplified treatment tends to underestimate the effectiveness of the permeation barriers in comparison to real world conditions. The reduced air movement over the surface of the primary emission source (e.g., particleboard underlayment) caused by the presence of the permeation barrier should enhance CH_2O concentration gradients near the surface of the emitter and thus reduce the $\text{CH}_2\text{OER}'$. A simple negative linear dependence of the $\text{CH}_2\text{OER}'$ on the CH_2O concentration below the barrier is also assumed.

$$\text{CH}_2\text{OER}' = -m[\text{CH}_2\text{O}]_{\text{BB}} + b \quad (7)$$

Analogous to equation 5, the $\text{CH}_2\text{OER}'$ at steady state is assumed to be greater than or equal to zero. Combining equations 6 and 7, the resultant emission model for a combination CH_2O source and permeation barrier is

$$\text{CH}_2\text{OER}' = (b - m \cdot [\text{CH}_2\text{O}]_{\text{SS}})/(1 + m/k) \quad (8)$$

Steady-State Formaldehyde Concentration Models Incorporating Source Emission Models

The potential contribution of CH_2O emission sources to indoor CH_2O concentrations ($\Delta[\text{CH}_2\text{O}]$) is estimated from the difference between the steady-state CH_2O concentration with various sources contained inside the compartment ($[\text{CH}_2\text{O}]_{\text{SS}}$) and the concentration outside the compartment ($[\text{CH}_2\text{O}]_0$).

$$\Delta[\text{CH}_2\text{O}] = [\text{CH}_2\text{O}]_{\text{SS}} - [\text{CH}_2\text{O}]_0 \quad (9)$$

$[\text{CH}_2\text{O}]_0$ is assumed to be a constant reflecting the CH_2O concentration outdoors or in neighboring compartments. $[\text{CH}_2\text{O}]_{\text{SS}}$ is estimated from pollutant concentration models (i.e., equations 2, 3) incorporating emitter models (i.e., equations 5, 8) for various CH_2O emission sources.

For combustion sources $[\text{CH}_2\text{O}]_{\text{SS}}$ is calculated directly using the single compartment CH_2O concentration model (equation 2); the CH_2OER of combustion sources is assumed to be constant, independent of the CH_2O vapor concentration. For solid emission sources with direct exposure inside the compartment, $[\text{CH}_2\text{O}]_{\text{SS}}$ is calculated from a combination of the indoor CH_2O concentration (equation 3) and emitter (equation 5) models.

$$[\text{CH}_2\text{O}]_{\text{SS}} = (A \cdot b + [\text{CH}_2\text{O}]_0)/(1 + mA) \quad (10)$$

where

A = Area/(PEX · VOL)

For solid sources separated from the indoor compartment by an intervening permeation barrier, $[CH_2O]_{SS}$ is calculated from a combination of the CH_2O concentration model (equation 3) and the emitter and permeation barrier model (equation 8).

$$[CH_2O]_{SS} = \frac{A \cdot b + [1 + (m/K)] \cdot [CH_2O]_0}{1 + (m/K) + mA} \quad (11)$$

In the case of a very inefficient permeation barrier (i.e., $K \gg 1$) equation 11 reverts back to equation 10. With a highly effective permeation barrier (i.e., $K \sim 0$), equation 11 reduces to

$$[CH_2O]_{SS} \approx [CH_2O]_0 \quad (12)$$

indicating that the CH_2O emitter has little contribution on the indoor CH_2O concentration.

For a single compartment with multiple CH_2O point sources (u) and area sources (v), $[CH_2O]_{SS}$ is determined using the following expression.

$$[CH_2O]_{SS} = [CH_2O]_0 + \sum_{i=1}^u (CH_2OER / (PEX \cdot VOL)) + \sum_{i=1}^v (CH_2OER' \cdot Area) / (PEX \cdot VOL) \quad (13)$$

For solid emission sources, appropriate emitter models are substituted for CH_2OER' .

Potential Impact of Formaldehyde Emission Sources on Steady-State Indoor Formaldehyde Concentrations

Substituting the average CH_2O emission rate data for combustion and solid emission sources into appropriate steady-state CH_2O concentration models, the potential contribution of individual sources to indoor CH_2O concentrations (i.e., $\Delta[CH_2O]$, equation 9) can be estimated. However, further assumptions concerning the general design of the indoor compartment are required. The length, width, and height of the compartment are assumed to be 4, 4, and 2.5 m, respectively. The compartment volume is thus 40 m^3 . The pollution exchange rate (PEX) is assumed to be 0.5 h^{-1} . This PEX is consistent with the results taken in the 40 home study in the Oak Ridge/Knoxville (TN) area in 1982-3 (Hawthorne et al., 1983). The CH_2O concentration outside of the compartment ($[CH_2O]_0$) is assumed to be 0.03 mg/m^3 . This concentration reflects a compromise between anticipated near-zero outdoor levels and the potential for residual CH_2O levels in adjacent indoor compartments.

For combustion sources, the CH_2O emission rate data (Table 1) is substituted into equation 2. The $\Delta[CH_2O]$ values calculated from equation 9 are listed in Table 4. The results indicate that for each combustion source a small contribution to the steady-state CH_2O concentration is anticipated. This hypothesis may be contingent, however, on several factors; consumer use patterns for cigarettes; duty cycle and local ventilation for gas stoves; and the duty cycle, design, and tuning of kerosene heaters. Certain kerosene heaters have been found to be strong CH_2O emitters under various tuning conditions (Girman, Allen et al., 1983).

For solid emission sources with direct exposure in the indoor atmosphere, CH_2O emission rate data (Table 2) is substituted into either equation 3 or equation 10. Equation 3 is typically used for weak emitting products where the CH_2O concentration dependence of the CH_2O emission rate has not been measured. The CH_2O emission rate is assumed to be constant, independent of CH_2O concentrations, thus maximizing the contribution of the emitter to the modeled CH_2O concentration. Equation 10 is used for pressed-wood products and UFFI where CH_2O concentration dependent emission models (i.e., equation 5) can be estimated. The slope and intercept values (i.e., m, b, equation 5) of the emitter model must be empirically determined (see Table 5). The pressed-wood product constants were determined from measurements of boards sampled primarily from U.S. industry in 1983. The measurements were taken when the boards were typically less than one year old. The UFFI constants were determined from measurements of 1.3 year old simulated wall panels (Hawthorne, 1981) foamed in 1980 (Osborn et al., 1981). It should be emphasized, however, that the specific age of the CH_2O emitters or the age dependence of the CH_2O emission rates from the CH_2O sources are not considered in the modeling. Calculations used to determine the average slope and intercept values for each product category are detailed in Appendix IV.

To use equations 3 and 10, additional assumptions are required concerning the area (m^2) of the solid CH_2O emission sources. Unfortunately, available annual survey data for product sales was difficult to relate to cumulative average quantities of individual furnishings actually contained in 'typical' detached U.S. housing. As a result, the selected area for each product was determined whenever possible according to common product use characteristics in an individual compartment. For example, the areas of carpeting and resilient flooring, and ceiling tiles were chosen to cover the entire floor and ceiling, respectively. For other home furnishings such as textiles and furniture, two different areas were chosen that vary by a factor of five to attempt to account for widely variable product usage. For furniture constructed with pressed-wood products, it is particularly difficult to estimate the effective emitting area because much of the surface is sealed with a variety of decorative permeation barriers.

For decorative paneling, definitive survey data for about the last decade is available for the approximate 25% of new home construction that contain paneling (Housing Industry Dynamics, 1980). However, remodeling and repair applications generally account for >20 times the sales of paneling for new home construction (Housing Industry Dynamics, 1980). Unfortunately, the average paneling use for remodeling and repair applications in homes that contain paneling is unavailable. As a result, it is difficult to estimate the cumulative quantity of decorative paneling that is present in an average home. In addition, the total CH_2O emissions from existent paneling will depend on decay rate for CH_2O emissions from each board, which could be highly variable from home to home. As a consequence, one wall of decorative paneling was chosen as the minimum quantity that would normally be present in a room for decorative purposes.

For UFFI, a surface area of 1.5 walls was selected as a compromise between corner and side rooms in a home that would contain two and one insulated exterior walls, respectively. A reduction in surface area of $1 m^2$ was also made for a window.

The specific areas assumed for each category of solid emission sources with direct indoor exposure and the $\Delta[CH_2O]$ values calculated using equation 9 are listed in Table 6. The results indicate that the contribution of carpeting, resilient flooring, textiles, and ceiling tiles are anticipated to be minimal. The contribution of furniture is expected to be highly variable, depending upon the category and quantity of pressed-wood products and the presence of permeation barriers. Medium density fiberboard is a particularly strong CH_2O emitter in uncovered form. The contribution of one wall of decorative hardwood plywood paneling on indoor CH_2O concentrations may be significant, especially if printed paneling is used. The contribution of UFFI, based upon CH_2O emission data from simulated wall panels without vapor barriers (Hawthorne, 1981), appears to be significant.

To evaluate the contribution of individual emission sources covered by permeation barriers, equation 11 and, subsequently, equation 9 are used. For equation 11, assumptions concerning the area of each CH_2O emission source, the CH_2O concentration dependence of each source (i.e., Table 5) and the CH_2O transport coefficient, K , for individual permeation barriers are required. Data for each parameter are only available for particleboard underlayment and specific decorative flooring materials. A comparison of the modeling results for the underlayment with no barrier, a carpet and carpet cushion barrier, and a resilient flooring barrier, are shown in Table 7. Permeation barriers, especially the resilient tile flooring, are anticipated to cause marked reductions in the contribution of particleboard underlayment to indoor CH_2O concentrations.

Other products that are covered by permeation barriers, such as softwood plywood subflooring, carpet cushion, and fibrous glass insulation, are generally weak emitters; the contribution to indoor CH_2O concentrations is anticipated to be small, independent of the presence of permeation barriers. Worst case calculations without permeation barriers using equation 3 indicate a $\Delta[CH_2O]$ of ≤ 0.01 ppm for all products (except particleboard underlayment) that are listed in Table 7. The low permeability of particleboard underlayment provides additional evidence for a minimal contribution of softwood plywood subflooring on indoor CH_2O concentrations. Additional calculations have also been made for fibrous glass attic insulation using a two compartment model with an attic temperature of $38^\circ C$. A maximum $\Delta[CH_2O]$ of about 0.02 ppm was estimated (Matthews, Westley, 1983).

SUMMARY: IDENTIFICATION OF SIGNIFICANT FORMALDEHYDE EMISSION SOURCES

Several conclusions can be drawn concerning the CH_2O emission characteristics of solid CH_2O emission sources. Urea-formaldehyde resin bonded products with high loading, such as UFFI, particleboard underlayment, and decorative paneling, are most likely to cause

significant increases in the indoor CH_2O concentration. Phenol formaldehyde resin bonded products, such as softwood plywood and fibrous glass insulation, are generally weak emitters that are anticipated to have a minimal contribution to indoor CH_2O concentrations. Formaldehyde resin bonded products with low loading, such as many textiles and furniture, should have a minimal contribution to indoor CH_2O concentrations unless their CH_2O emission rates are much larger than those of other high loading products in the floor, walls and ceiling. Products with minimal CH_2O content, such as most carpet, carpet cushion, resilient tile flooring, and non-fibrous glass ceiling tiles should not cause significant increases in indoor CH_2O concentrations.

The modeling of CH_2O emission rate data for combustion sources (i.e., cigarettes, kerosene heaters, and gas stoves) indicate that the average contribution to indoor CH_2O concentrations is anticipated to be small. However, widely variable consumer use patterns for cigarettes, variable duty cycles for gas stoves, and variable design, tuning and duty cycles for kerosene heaters make definitive conclusions impossible. More detailed data and time dependent models would be required to estimate the time dependent (e.g., peak) exposures. Combustion sources presumably aggravate existing problems in indoor environments with unacceptable CH_2O concentrations because the CH_2O emission rates are insensitive to indoor CH_2O concentrations. Unlike solid emission sources, combustion sources are anticipated to emit CH_2O at similar levels in both low and high concentration environments.

POSSIBLE CORRECTIVE ACTIONS FOR UNACCEPTABLE FORMALDEHYDE CONCENTRATIONS IN INDOOR ENVIRONMENTS

Several corrective measures of varying practicality exist for the reduction of CH_2O in indoor environments with unacceptable CH_2O concentrations. The general categories of corrective actions include:

1. increased removal rate of CH_2O vapor with increased air exchange or with air filtering devices,
2. removal of CH_2O emission sources or replacement with low emission products,
3. aging of solid emission sources,
4. permeation barriers between the emission source and indoor atmosphere, and
5. chemical (i.e., ammonia) fumigation.

The removal of CH_2O vapor, aging of sources, and chemical fumigation are general corrective measures that contribute on a variety of CH_2O emission sources. The removal or replacement of emission sources and installation of permeation barriers are generally source-specific corrective measures. The effectiveness of any single or collection of corrective measures will depend on the emission characteristics of the sources contained in an indoor environment, the ventilation characteristics of the environment, and the acceptability of various CH_2O concentrations. Clearly, if acceptable CH_2O concentrations are lowered, more exhaustive and costly corrective measures are required.

Evaluation of Corrective Measures Using Single Compartment Formaldehyde Concentration Modeling and Comparative Field Data

Field data taken under a controlled experimental design are minimal for many corrective measures. As a result, the single compartment CH_2O concentration modeling developed in this report will be used in combination with available field data to estimate the potential effectiveness of various control measures. To simulate the interaction of multiple CH_2O emission sources in an indoor compartment and their combined effect on the steady-state indoor CH_2O concentration, equation 13 and equation 9 are used. To simplify the multiple emitter treatment, only solid emission sources with significant emission potential are incorporated into the model. The sources, source areas, and calculated $\Delta[\text{CH}_2\text{O}]$ values as a function of PEX are summarized in Table 8.

The range of CH_2O levels predicted by the CH_2O concentration modeling for a combination of pressed-wood and UFFI sources (i.e., 'All Emitters', Table 8) and just pressed-wood sources (i.e., 'UFFI Removed', Table 8) are consistent with the range of CH_2O concentrations observed in 0-5 year old homes investigated in the Oak Ridge National Laboratory (ORNL) 40 home study (Table 9). The closest correlation between the modeled and measured CH_2O concentrations would be anticipated for recently built homes where the pressed-wood products and UFFI would be most similar to those evaluated in laboratory studies.

Older homes (i.e., >5 year) in the 40 home study had consistently lower CH₂O concentrations (Table 9). This is presumably evidence for the aging of CH₂O resin containing emission sources. Additional factors such as tighter home construction in newer homes may also be involved. Formaldehyde emission decay studies of pressed-wood products under controlled temperature, humidity, and CH₂O concentration are in progress (Matthews, Reed, 1984). Initial results indicate that the decay rate will be a function of product type and environmental conditions.

The potential effect of increased ventilation and several sequential corrective measures including installation of permeation barriers, source replacement, and source removal have also been estimated using the indoor CH₂O concentration modeling (Table 8). Increases in ventilation cause significant reductions in the calculated CH₂O concentrations. However, the decrease in CH₂O concentration is substantially less than proportional to the increase in PEX. In addition, the results of the CH₂O concentration modeling demonstrate an insensitivity to a sequential series of corrective measures aimed at individual sources when several significant emission sources are present in the compartment. Several corrective measures are required to achieve marked reductions in the modeled CH₂O concentrations. These phenomena are consistent with the negative CH₂O concentration dependence of the CH₂O emission rates observed for solid CH₂O resin containing products. As the CH₂O concentration is reduced due to increased PEX, installation of permeation barriers, source removal or source replacement, the emission rate of the remaining solid sources is increased, thus reducing the effectiveness of the corrective action.

The insensitivity of indoor CH₂O concentrations to increases in air exchange rate has been observed in measurements of a mobile home with a newly installed heat exchanger (Table 10 (Zieman, 1982)). An increase in air exchange rate of 2.2 h⁻¹ using the heat exchanger resulted in only about a factor of two decrease in CH₂O concentration. Unfortunately, trace gas measurements of the PEX were not made before and during the operation of the heat exchanger. However, a large increase in PEX was probably incurred with the heat exchanger because the residual PEX of modern mobile homes is generally low (i.e., 0.26 ± 0.12 (Jewell, 1982)).

Permeation Barriers

A variety of permeation barriers have been shown to effectively reduce CH₂O emissions from individual sources. Effective barriers generally consist of a thick liquid-applied coating or solid overlay that forms a continuous barrier to the transport of water vapor. The efficiency and availability of permeation barriers for various solid emission sources is highly variable. For particleboard underlayment, resilient tile flooring (Whippie, 1983) and floor sealing paints (Fountain, 1983) have been shown to be effective permeation barriers. Factors of 5 to 10 reductions have been measured for both barriers. However, in remedial applications, the accessibility of the entire underlayment surface can be a problem.

For pressed-wood furniture, a variety of coatings and overlays exist for the reduction of CH₂O emissions (Marutzky, 1981). In nations such as West Germany that grade pressed-wood products with respect to CH₂O emissions prior to consumer use, a list of coatings and overlays are specified by the government to upgrade high emission products to lower emission levels. However, in remedial applications only non-decorative surfaces can be effectively sealed without significant modification to the decorative appearance of the product.

For decorative hardwood plywood paneling, no coatings were found available to the consumer that do not significantly alter the appearance of the product. However, factory applied products, such as vinyl overlays, can be very effective in the reduction of CH₂O emissions from the decorative side of the panel.

The effectiveness of remedial applied permeation barriers for UFFI is less understood than for pressed-wood products. The sealing of large holes or cracks is generally recommended to reduce the convective transport of CH₂O from UFFI into the indoor environment (Bowen, 1981). Continuous plastic vapor barriers can be expensive to install as a remedial measure. Vapor retardant paints that can be conveniently applied to the interior gypsum board surface have not been critically studied (Table 11). Although standard latex paint has been shown to be ineffective in reducing CH₂O transport (Hawthorne, 1981), water vapor permeation experiments indicate that vapor retarder latex paint and some oil paints may be an order of magnitude less permeable than standard latex paint (ASHRAE, 1981). The accessibility of all interior surfaces adjoining the UFFI, however, may be a serious problem.

Ammonia Fumigation

The effectiveness of ammonia (NH_3) fumigation techniques in the reduction of indoor CH_2O concentrations has been primarily studied in mobile homes. The general protocol is to fumigate the interior atmosphere of a dwelling for about one day at $>30^\circ\text{C}$ with several thousand ppm NH_3 concentrations developed using open pans of 28% NH_3 solution (Jewell, 1982). Although a critical evaluation of the experimental parameters involved in the fumigation procedure has not been performed, it is generally assumed that high temperatures, high NH_3 concentrations, and lengthy exposure periods produce the best reduction in indoor CH_2O concentration. Measurements performed by L. R. Newton of Georgia Pacific in seven mobile homes over a half year period indicate about an 80% reduction in CH_2O concentration (Newton, 1983). Data taken by R. A. Jewell (1983) of Weyerhaeuser in 12 mobile homes over a one year period indicate about a 70% reduction in CH_2O concentration. A recent follow up by Jewell (1984) in seven of the 12 mobile homes ~3.5 years after fumigation suggests that the NH_3 treatment may result in long term reductions in CH_2O concentration. Five of the seven revisited homes had CH_2O concentrations averaging 60% lower than the levels prior to fumigation. However, the apparent long term effectiveness of the NH_3 treatment over a 3.5 year period may be the results of normal product aging which were not separated out of the analysis.

The effectiveness of NH_3 fumigation in the reduction of CH_2O emissions from UFFI has also been investigated in laboratory and field studies. The laboratory work by H. D. Gessner (1983) has been performed by monitoring steady-state CH_2O concentrations inside polyethylene lined barrels containing untreated and NH_3 -treated UFFI. Although approximate order of magnitude reductions in CH_2O concentration are observed for a couple of months following fumigation, the long term effectiveness of the treatment is unclear. Several field studies have been performed in Europe where UFFI has been used extensively in schools and public buildings. Unfortunately, most of the results of NH_3 treatments are unavailable because of legal problems. The results of NH_3 fumigation in the St. Thomas Moore School in England (Barret, 1983) generally confirms the work by Gessner. With a combination of remedial measures including caulking and NH_3 fumigation, the CH_2O concentration was reduced from 0.6 ppm to 0.08 ppm. Following a second NH_3 fumigation 13 months later, the CH_2O concentration was 0.03 ppm. The long term effectiveness of the treatment remains unclear, but the use of multiple treatments on an annual basis may be a viable remedial action.

SUMMARY: EFFECTIVENESS OF FORMALDEHYDE CORRECTIVE ACTIONS FOR DWELLINGS WITH UNACCEPTABLE FORMALDEHYDE CONCENTRATIONS

The potential cost and efficiency of various corrective measures for reduction of indoor CH_2O concentrations is difficult to estimate. The simplest solution for solid emission sources is product aging. Data from the ORNL 40 home study (Dudney, 1983) indicates that the vast majority of study houses greater than five years old remain below 0.1 ppm CH_2O , the guideline established by the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE Std., 1981). However, the results of this limited study may not represent all U.S. housing.

Increased air infiltration can partially reduce indoor CH_2O concentrations. Large improvements (e.g., greater than a factor of 2) are probably difficult to achieve during heating or cooling seasons due to energy costs and increased CH_2O emission rates from CH_2O resin bonded products as CH_2O concentrations are reduced.

The removal of CH_2O emission sources can be expensive for products such as UFFI or particleboard underlayment where wall or floor destructive procedures are required. The indoor CH_2O concentration modeling developed in this report suggests that individual source removal from a dwelling containing several significant CH_2O emission sources may be only moderately effective (e.g., less than a factor of two) in reducing the indoor CH_2O concentration.

Permeation barriers are effective for solid emission sources that are both accessible and have non-decorative surfaces. Such barriers are most easily applied in the construction of new homes or home furnishings as opposed to remedial actions.

Current field data for NH_3 fumigation suggests that 3 to 10-fold reductions in CH_2O concentrations can be temporarily achieved. The duration of the effectiveness of such treatments may be dependent on the CH_2O emission source and treatment parameters. In mobile homes large reductions in CH_2O concentrations have been clearly observed over 0.5 to 1.0 year periods. Available data for UFFI insulated dwellings are inconclusive, but suggest that the

NH₃ may be effective for periods of less than one year. For either pressed-wood or UFFI emission sources, repeated NH₃ treatments as needed on an annual basis may be a viable solution for a CH₂O emission problem until natural aging phenomena have reduced the emissions to acceptable levels.

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ACKNOWLEDGEMENTS

Research sponsored jointly by the U.S. Consumer Product Safety Commission under Interagency Agreement CPSC-IAQ-82-1297 and the Office of Health and Environmental Research, U.S. Department of Energy, under contract DE-AC05-84OR21400 with the Martin Marietta Energy Systems, Inc. The opinions expressed in this article are those of the authors and do not necessarily represent the views of the sponsoring agencies.

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APPENDIX I: UNITS AND CONVERSIONS

- [1] Formaldehyde concentration at 23°C
 $1 \text{ ppm} = 1.24 \text{ mg/m}^3 = 1240 \text{ } \mu\text{g/m}^3 = 7.74 \times 10^{-8} \text{ lbs/ft}^3$
- [2] Emission Rate
 $1 \text{ mg/m}^2\text{h} = 0.28 \text{ } \mu\text{g/m}^2\text{s} = 2.05 \times 10^{-7} \text{ lbs/ft}^2\text{h}$
- [3] Transport Rate
 $1 \text{ m/h} = 0.017 \text{ m/s} = 5.08 \times 10^{-3} \text{ ft/s}$
- [4] Air Exchange Rate
 $1 \text{ Compartment Volume/h} = 0.017 \text{ Compartment Volume/s}$
- [5] Energy
 $1 \text{ Btu} = 1.06 \text{ Kjoules}$
- [6] Loading
 $1 \text{ m}^2/\text{m}^3 = 0.30 \text{ ft}^2/\text{ft}^3$

APPENDIX II: DETERMINATION OF SLOPE AND INTERCEPT VALUES FOR PRESSED-WOOD PRODUCTS AND UFFI LINEAR FORMALDEHYDE MODELS

A simple negative linear dependence of the CH₂O emission rate of pressed-wood products and UFFI on CH₂O concentration is assumed (Eq. 5). For each product this linear model is described by two constants, the slope and intercept value.

The slope values for pressed-wood products and urea-formaldehyde foam insulation (UFFI) (Table 5) were determined from linear least squares analyses of CH₂O emission rate data (i.e., dependent variable) as a function of CH₂O concentration (i.e., independent variable). For pressed-wood products, the CH₂O emission rate data at a variety of CH₂O concentrations were determined from environmental chamber experiments where the CH₂O concentration was indirectly controlled through variation in product loading and air exchange rate (Matthews, Hawthorne, 1983). The results for each category of pressed-wood products listed in Table 5 represent the average slope for typically three or more boards sampled from U.S. industry in 1982-83. With UFFI, CH₂O emission rate data was measured from insulation encased in simulated exterior wall panels. The air exchange rate through a chamber on the gypsum board side of the wall panels was varied to determine the CH₂O emission rate at different CH₂O concentrations. The results listed in Table 5 represent the average slope for measurements of nine wall panels (Hawthorne, 1981).

The intercept values (i.e., of the dependent variable) for pressed-wood products were calculated using 1) the slopes determined from the linear regression analysis of the environmental chamber data mentioned previously and 2) the results of a pressed-wood survey involving more than 100 boards sampled from U.S. industry in 1983 (Matthews, Reed, 1983). The survey was conducted using the ORNL-developed formaldehyde surface emission monitor (FSEM). A strong, approximately 1 to 1 correlation between CH₂O emission rate data taken with the FSEM and with the environmental chamber at 23°C, 50% relative humidity (RH), and 0.1 ppm CH₂O has been observed for a variety of pressed-wood products (Matthews, Hawthorne, 1984, and Matthews, Reed, 1984). Substituting 1) the average FSEM data from Table 2 for the assumed CH₂O emission rate at 0.1 ppm CH₂O (i.e., 0.124 mg/m³) and 2) the average slope determined from environmental chamber experiments (i.e., Table 5) in equation 5, the intercept for the dependent variable can be calculated.

$$b(\text{mg/m}^2\text{h}) = \text{CH}_2\text{OER}' \cdot 0.125 \text{ mg/m}^3 + m(\text{m/h}) \cdot 0.125 (\text{mg/m}^3) \quad (\text{A1})$$

For UFFI, independent survey data of a large number of simulated wall panels was unavailable. The intercept for the dependent variable was calculated as the average of the intercepts determined from measurements of the nine wall panels.

*The intermethod correlation between the FSEM and environmental chamber is strongly dependent on equal conditioning of the pressed-wood specimens used in both experiments at 23°C, 50% RH, and <0.15 ppm CH₂O for >7 days prior to measurement (Matthews, Hawthorne, 1984). Such precautions were followed in both the FSEM and environmental chamber experiments.

TABLE 1
Formaldehyde Emission Rates of Combustion Sources

Product	Duty Cycle ^a	Formaldehyde Emission Rate (mg/h)	
		Measured	Average Over 24 h
Gas Burner	1.0 h/day	16 ± 10 ^b 4.3 ± 2.6 ^c	0.67 ± 0.41 0.18 ± 0.11
Gas Oven	0.7 h/day	23 ± 3.4 ^b	0.67 ± 0.10
Kerosene Heater			
-Convective	8 h/day	1.0 ± 0.66 ^d	0.33 ± 0.22
-Radiant	8 h/day	4.0 ± 2.0 ^d	1.3 ± 0.66
Cigarettes	10 cig/day	0.97 ± 0.06 ^e 1.44 ^f	0.40 ± 0.03 0.60

^aEstimation of duty cycle described in text ^bTraynor et al., 1982

^cMoschandreas et al., 1983 ^dTraynor et al., 1983. Data for new heaters (i.e., <1 yr old)

^eSpengler, 1981 ^fWeber et al., 1979

TABLE 2
Formaldehyde Emission Rates from CH₂O Resin Containing Products with Direct Exposure in Indoor Environments

Product	Formaldehyde Emission Rate (mg/m ² h)	
	Average	Range
Non-Apparel Textiles ^a		
-Drapery	(<0.01)	<0.01-0.02
-Upholstery	(<0.01)	<0.01
Apparel Textiles (unwashed) ^a	(0.01)	<0.01-0.02
Carpeting ^a	(<0.01)	<0.01
Ceiling Tiles ^b	0.01±0.01	<0.01-0.02
Resilient Flooring ^c	<0.01	<0.01
Furniture (uncovered boards)		
-Industrial Particleboard ^d	0.31±0.14	0.15-0.62
-Medium Density Fiberboard ^d	1.5±0.51	0.57-2.3
Decorative Hardwood		
Plywood Paneling ^d		
-Print Overlay	0.28±0.20	0.05-0.63
-Paper Overlay	0.11±0.07	0.03-0.27
-Domestic Veneer Overlay	0.12±0.04	0.07-0.24
Urea-Formaldehyde		
Foam Insulation ^e	0.23±0.19	0.05-0.80

^aPickrell et al., 1983. Average data calculated from the midpoint in the range for all product subgroups in each product category. ^bMatthews, Westley, 1983.

^cMatthews, Reed et al., 1984. ^dMatthews, Reed et al., 1983.

^eUFFI is normally encased behind gypsum wallboard. It is treated as an emitter with direct indoor exposure because CH₂O emission rate data were taken from simulated exterior wall panels (Hawthorne et al, 1981).

TABLE 3
Formaldehyde Emission Rates from CH₂O Resin Containing Products
with Indirect Exposure in Indoor Environments through Permeation Barriers

Product	Formaldehyde Emission Rate (mg/m ² h)	
	Average	Range
Carpet Cushion ^a	0.01 ± 0.01	<0.01 - 0.02
Fibrous Glass Insulation ^b	0.02 ± 0.01	<0.01 - 0.02
Softwood Plywood Subflooring ^c	0.02 ± 0.01	0.01 - 0.03
Particleboard Underlayment ^d	0.30 ± 0.22	0.11 - 0.78

^aMatthews, Reed et al., 1984.

^bMatthews, Westley, 1983.

^cMatthews, Hawthorne et al., 1983.

^dMatthews, Reed et al., 1983.

TABLE 4
Potential 24-h Average Contribution of Combustion Sources
to Indoor CH₂O Concentrations

Product	Δ[CH ₂ O](ppm)
Gas Stove	
-Burner	0.03, ^a 0.01 ^b
-Oven	0.03 ^a
Kerosene Heater	
-Convective	0.01 ^c
-Radiant	0.05 ^c
Cigarettes	0.02 ^d

^aCH₂O emission rate data taken from Traynor et al., 1982.

^bCH₂O emission rate data taken from Moschandreas et al., 1983.

^cCH₂O emission rate data taken from Traynor et al., 1983.

^dCH₂O emission rate data averaged from Spengler, 1981, and Weber, 1979.

TABLE 5
Summary of Slope and Intercept Constants for Linear CH₂O
Emission Models for Pressed-Wood Products and UFFI^a

Product	Slope (m/h) ^b	Intercept (mg/m ² h)
Particleboard Underlayment	-0.60 ± 0.23	0.38 ± 0.03
Industrial Particleboard	-0.47 ± 0.18	0.37 ± 0.03
Hardwood Plywood Paneling		
-Print Overlay	-0.40 ± 0.09	0.33 ± 0.01
-Paper Overlay	-0.22 ± 0.10	0.14 ± 0.01
-Domestic Veneer Overlay	-0.27 ± 0.13	0.15 ± 0.02
Medium Density Fiberboard	-0.94 ± 0.06	1.6 ± 0.1
Urea Formaldehyde Foam Insulation	-0.46 ± 0.47	0.34 ± 0.34

^aCalculations for the determination of the slope and intercept values described in Appendix II.

^bNote: substitute positive slope values into equations 5, 7, 8, 10, or 11 because the negative sign is incorporated into the equations.

TABLE 6
Potential Contribution of Solid Emission Sources with Direct
Exposure in Indoor Environments to Indoor CH₂O Concentrations

Product	Area (m ²)	Δ[CH ₂ O] (ppm)
Textiles		
-Non-Apparel	5	<0.01
-Apparel	25	0.01
	5	<0.01
	25	0.01
Carpeting ^a	16	<0.01
Ceiling Tiles ^b	16	<0.01
Resilient Flooring ^c	16	<0.01
Furniture (uncovered board)		
-Industrial Particleboard ^d	1.0	0.01
	5.0	0.06
-Medium Density Fiberboard	1.0	0.06
	5.0	0.25
Decorative Paneling ^d		
-Print Overlay	10	0.11
-Paper Overlay	10	0.05
-Domestic Veneer Overlay	10	0.05
(Urea Formaldehyde Foam Insulation) ^e	14	0.14

^bCH₂O emission rate data taken from Matthews, Westley et al., 1983.

^cCH₂O emission rate data taken from Matthews, Reed et al., 1984.

^dCH₂O emission rate data taken from Matthews, Reed et al., 1983.

^efCH₂O emission rate data taken from Hawthorne, 1981.

TABLE 7
Potential Contribution of Solid Emission Sources Separated from the
Indoor Atmosphere by Permeation Barriers to Indoor CH₂O Concentrations

Product	Barrier	K (m/h)	Area (m ²)	Δ[CH ₂ O] (ppm)
Particleboard	None	∞	16	0.16
Underlayment	Carpets & Cushion	0.43 ^a	16	0.08
	Tile	0.003 ^a	16	<0.01
Softwood Plywood	Particleboard	0.002	16	<0.01
Subflooring	Underlayment			
Carpets Cushion	Carpets	-	16	<0.01 ^c
Fibrous Glass	Gypsum Board	0.57 ^b	16	<0.01 ^c
Ceiling Insulation				
Fibrous Glass	Gypsum Board ^b	<0.57 ^{b,d}	14	<0.01 ^c
Wall Insulation				

^aMatthews, Reed et al., 1984.

^bHawthorne, 1981.

^cΔ[CH₂O] calculated with worst case assumption that K=∞ for the barrier.

^dThe effective K values for non-continuous barriers such as Kraft paper or foil behind gypsum board are unavailable.

TABLE 8
Potential Impact of Multiple CH₂O Emission Sources on Indoor CH₂O Concentrations
(Δ[CH₂O], ppm) as a Function of Air Infiltration Rate and Sequential Corrective Actions

PEX (h ⁻¹)	All Emitters ^a	UFFI Removed	Tile Flooring Installed	Replacement with Low Emission Paneling ^b	MDF Removed
0.25	0.38	0.32	0.28	0.20	0.13
0.50	0.28	0.21	0.17	0.12	0.07
1.0	0.18	0.13	0.10	0.07	0.04
2.5	0.09	0.06	0.04	0.03	0.02
5.0	0.05	0.03	0.02	0.01	0.01

- ^a1. Urea-Formaldehyde Foam Insulation: 1.5 walls, 14 m²
2. Carpet Covered Particleboard Underlayment: 16 m²
3. Decorative Hardwood Plywood Paneling: 1 wall, 10 m² print overlay
4. Cupboards, Industrial Particleboard: 2 m²
5. Furniture, Medium Density Fiberboard: 1 m²

^bReplacement paneling with domestic veneer overlay.

TABLE 9
Frequency of Room-Average CH₂O Concentrations Determined from Measurements
Taken During Multiple Visits to Homes in the ORNL 40 Home Study (Dudney, 1983)

		Average Formaldehyde Concentration (ppm)									
		<0.025	0.025-0.075	0.075-0.125	0.125-0.175	0.175-0.225	0.225-0.275	0.275-0.325	0.325-0.375	>0.375	
Homes Containing											
UFFI											
<5 years old	85	71	91	57	32	8	3	1	0		
>5 years old	86	45	18	11	1	1	0	3	0		
Homes Without											
UFFI											
<5 years old	67	64	63	34	9	22	9	13	12		
>5 years old	133	143	55	8	4	0	0	0	0		

TABLE 10
Effect of Increased Air Exchange Rate Due to Operation of a
Heat Exchanger on the CH₂O Concentration in a Mobile Home (Zieman, 1982)

Increase in ACH (h ⁻¹)	Relative CH ₂ O concentration*
0	1
1.1	0.71 ± 0.07
1.1	0.82 ± 0.08
1.1	0.81 ± 0.18
1.6	0.67 ± 0.07
2.2	0.29 ± 0.09
2.2	0.59 ± 0.15

*A minimum 10% coefficient of variation was assumed.

TABLE 11
Summary of Available CH₂O and H₂O Permeation Data
for Latex and Oil Based Products

Product	Perms ^a	K _{H₂O} (m/h) ^b	K _{CH₂O} (m/h) ^c
Unpainted Gypsum Board	-	-	0.62
Std. Latex Painted Gypsum Board	-	-	0.57
Std. Latex Paints	5.5-8.6	0.15-0.24	-
Vapor Retarder Latex Paint	0.45	0.013	-
Oil Paints	0.5-4.0	0.014-0.11	-

^aASHRAE, 1981

^bCalculated H₂O transport coefficients (Hawthorne, 1981)

^cMeasured CH₂O transport coefficients (Hawthorne, 1981)

SINGLE INDOOR COMPARTMENT MODEL

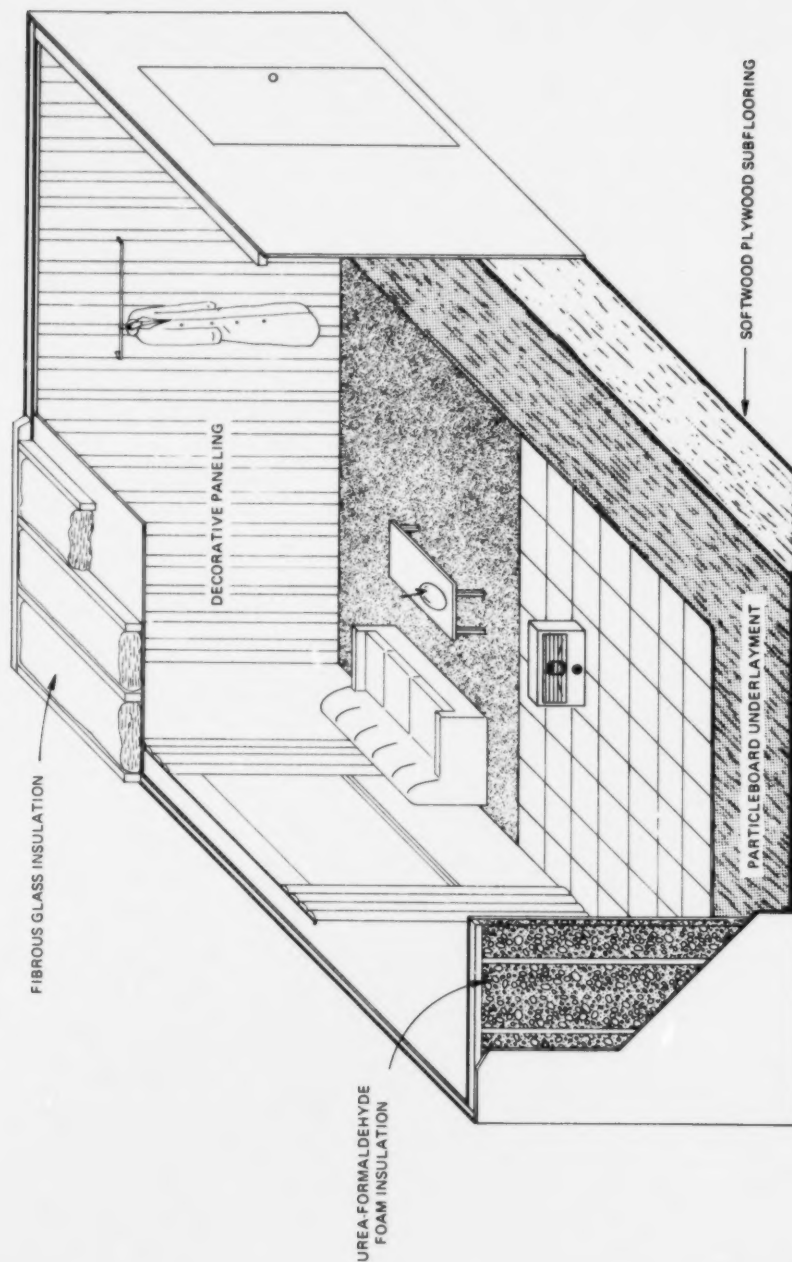


Figure 1.

Ventilation and Body Odor

P.O. Fanger, D. Sc. B. Berg-Munch

INTRODUCTION

Body odor is the major pollutant in many spaces in practice. Such spaces comprise lecture halls, class rooms, theatres, and meeting rooms where smoking is prohibited. The spaces are often ventilated constantly corresponding to maximum occupancy. When such a space is unoccupied or lightly occupied the room is overventilated and energy is wasted. Other and more energy conserving ventilation strategies should be considered to optimize the energy utilization. It seems rational to ventilate a space to maintain the body odor intensity at a given maximum permissible level. This raises two questions: how can body odor be quantified and measured, and what is an acceptable odor level? The aim of this paper is to answer these questions.

BODY ODOR

Body odor originates from sweat and sebaceous secretions from the skin, foul breath, and gases from the digestive tract. Body odor is a mixture of odors from a wide range of organic gases in small concentrations, difficult to measure. Since man is exhaling carbon dioxide in large quantities, CO_2 may be a useful index of human occupancy and of body odor intensity. The odor emission from the body shows large individual differences and depends on diet, activity, and personal hygiene, i.e. bathing habits, frequency of clothing change, etc.

People vary also in their response to body odor. Some do not seem to object while others find it most objectionable. During the 19th century a common belief existed that the human body emitted a poisonous substance (anthropotoxin) that caused a threat to man's health in densely occupied spaces. This theory was disproved early this century. The malaise frequently occurring in crowded assembly halls was shown to be attributable to warmth alone.

Although not poisonous, body odor may evoke a feeling of nausea and loss of appetite in some people [1]. But the main objection to body odor is the subjective discomfort. In general, people find strong body odor unpleasant, and it is the aim of ventilation in densely occupied spaces to dilute the odor intensity to a level where it is acceptable to most people. Body odor is especially noticeable by persons entering a space (visitors). The sense of smell is quickly fatigued or adapted, and on that account which is readily noticeable, or even unpleasant to a newcomer, may be unnoticed by occupants who have been exposed to it for a few minutes. The quick adaptation may also explain why man is less bothered by his own body odor. He is exposed to it for long periods by inhaling air contaminated by odor from his own body.

Corresponding to the quick adaptation of the sense of smell there occurs a quick restoration when exposed to clean air. An occupant adapted to a strong body odor in a space will, when reentering after having left the space for a few minutes, feel the same strong odor as a visitor. This is one reason why it has been common practice to design ventilation systems which provide body odor levels acceptable for visitors rather than just for occupants.

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The conclusions of Yaglou [2,3] from his studies 1936-37 have had a dominating influence on ventilating engineering. During 45 years standards and handbook recommendations in many parts of the world have been based on his work.

Yaglou's studies took place in a 40 m³ experimental chamber where temperature, humidity and ventilation rate could be controlled. The chamber was occupied for 3½ hours by 3, 7 or 14 occupants at each ventilation rate. Every hour the odor intensity in the chamber was estimated by judges who, one at a time, visited the chamber for a few moments. A 6-point psycho-physical scale was used by the judges to quantify the odor intensity: 0 (None), 1 (Definite), 2 (Moderate), 3 (Strong), 4 (Very Strong), 5 (Overpowering). The major group of occupants studied consisted of 177 sedentary men and women of average socio-economic status including students, office workers and housewives, who had their last bath at an average of 2.2 days before the experiment.

Yaglou decided arbitrarily to use the mean vote 2, i.e., 'moderate' odor, as an acceptable odor intensity. Fig. 1 shows the corresponding required ventilation rate derived from his data. The curve represented Yaglou's first surprising conclusion. It showed that a much higher ventilation rate (per person) was required when the chamber was densely occupied than when it was sparsely occupied. A doubling of the number of persons in a space required nearly a quadruplication of the outdoor supply air.

Yaglou [2] reports another surprising observation. When the occupants left the chamber and the ventilation was turned off, the odor intensity fell dramatically from 'strong' to 'moderate' in a few minutes. Yaglou named this observation 'spontaneous disappearance of body odor'. He claimed that body odor is very instable, and he suggested this instability as an explanation to the effect of occupant density on required ventilation rate.

A third conclusion of Yaglou was that carbon dioxide exhaled by occupants proved to be an unreliable index of body odor.

The present experiments were planned to check Yaglou's conclusions and to establish a rational basis for ventilation of spaces where body odor is the major pollutant.

METHOD

The experiments took place in two identical auditoria at the Technical University of Denmark (12 years old). The auditoria were modified to be suited for experiments. The ventilation system was changed so the outdoor air flow rate could be maintained at any level up to 4700 m³/h. The supply air was discharged through ceiling diffusers and the return inlets were situated in the floor under the chairs. Equipment and instrumentation were installed to measure air change, carbon dioxide, temperature, and humidity in the space. Each auditorium was designed for 172 occupants and had a volume of 850 m³. The experiments took place during normal lessons where the experimental auditoria were occupied by 41-216 male engineering students, who had had their last bath at an average of 0.7 days before the experiment. During all the experiments more than one thousand persons served as occupants. Ten minutes before the end of each 35-min lecture period ten judges entered the space and were questioned concerning their acceptance of body odor (see Fig. 2). Furthermore, they were asked to evaluate the odor intensity on the scale shown in Fig. 3. Both responses were based on the immediate impression of each judge when entering the space. The judges comprised 48 male and 41 female students. On average each judge participated in 22 experiments.

A total of 200 experiments were performed at ventilation rates of 0.4-26 l/s·person, with an air space per occupants of 4-21 m³ and with air temperatures of 17-26°C.

RESULTS

Preliminary results for 95 experiments at moderate air temperatures (17-22°C) are reported in this paper. Fig. 4 shows the odor intensity judged by the visitors as a function of the carbon dioxide concentration. There was no significant influence of air space per occupant on the odor intensity. Yaglou did not report the carbon dioxide concentrations but they can be estimated, and Fig. 4 shows how the odor intensity would be predicted based on Yaglou's data. There is an obvious large difference compared to the rather close odor/CO₂ relation established in the present study.

Fig. 5 shows the relation between the percentage of dissatisfied, i.e., those visitors who judged the odor to be unacceptable, and the odor intensity. It is obvious that there is a close relationship between the two subjective judgments.

Fig. 6 shows the percentage of dissatisfied as a function of the CO_2 concentration. For comparison is shown a line based on an analysis of the results of Cain et al. [4], who recently studied body odor in a 27 m^3 experimental chamber occupied by 4, 8 or 12 subjects and ventilated at four different rates. During 47 one-hour experiments the odor was judged every 15 minutes by judges at a sniffing station outside the chamber. The dotted line in Fig. 6 is based on the reported acceptances during Cain's experiments at low humidity, and calculated CO_2 concentrations, assuming a CO_2 production of $16 \text{ l/h}\cdot\text{person}$.

DISCUSSION

Neither of Yaglou's three conclusions could be confirmed in the present experiments. No significant influence of crowding (space volume per occupant) on the required ventilation rate was found (Fig. 4). This agrees with results by Cain et al. [4].

How could it then be explained that Yaglou found a crowding effect (Fig. 1)? The most likely explanation may be the infiltration of air to his small experimental chamber caused by the numerous door openings, when his judges, one at a time, were visiting the chamber. The decreased ventilation efficiency at increased ventilation rate may also contribute to the explanation.

The instability of body odor was disproven by Yaglou's own data [3]. If body odor should disappear spontaneously (in a few minutes) the logical consequence is that a steady-state level of odor should also occur spontaneously (in a few minutes). But Yaglou claims that it took at least one hour before steady-state conditions were reached, and this agrees with the data by Cain et al. [4]. Body odor seems to be rather stable. This is also indicated by the relationship established in the present study between the stable gas, carbon dioxide, and the odor intensity (Fig. 4).

Carbon dioxide seems to be a reasonable index of body odor emitted by the occupants investigated (Fig. 4). For other groups of occupants of another age, sex, national geographic origin, diet, hygienic standard, and at other activities and temperatures there may be other relations between body odor intensity and CO_2 concentrations.

Fig. 6 shows the percentage of dissatisfied as a function of CO_2 . The term 'percentage of dissatisfied' has been used by Fanger in several earlier studies [5,6] to express thermal discomfort. It has proven to be a rational and easily understandable way of expressing the impact of an environmental factor on man. For practical applications any percentage of dissatisfied may be selected according to the economy. Fig. 6 will then provide the corresponding CO_2 which may be used for the design of the ventilation system and for setting up a strategy to ventilate the space during the day. The ventilation system may also be controlled to maintain a constant CO_2 percent in the space.

The present results (Fig. 6) show that a substantial part of the population is quite sensitive to body odor, and high ventilation rates are required to satisfy this group. This agrees well with the results of Cain et al. [4]. ASHRAE's new ventilation standard [7] defines acceptable air quality as a condition where the air quality is accepted by at least 80% of the population (20% dissatisfied). The present results show (Fig. 6) that 20% dissatisfied correspond to a CO_2 concentration of 0.10% and a required steady-state ventilation rate of $7 \text{ l/s}\cdot\text{person}$. This is nearly three times higher than the ventilation rate of $2.5 \text{ l/s}\cdot\text{person}$ in the ASHRAE standard. Fig. 6 predicts as many as 50% dissatisfied at a ventilation rate of $2.5 \text{ l/s}\cdot\text{person}$. It is obvious from the present study that much higher ventilation rates than recently recommended will be required to satisfy visitors.

The curve in Fig. 6 has a low slope, i.e., it is difficult and expensive to satisfy the most sensitive. Some complaints of unacceptable odor intensity may therefore be expected in practice even at rather high ventilation rates.

Yaglou selected arbitrarily a limit on the odor intensity scale of 2 corresponding to 'moderate'. This would create as many as 32% dissatisfied among our judges according to Fig. 5. Yaglou's ambition for air quality was obviously rather low. Still his criterion caused rather high recommended ventilation rates due to the lower hygienic standard of his occupants.

The present study was performed at an outdoor CO_2 level of 0.035%. At a higher level of outdoor carbon dioxide, all CO_2 percentages in Figs. 4 and 6 should be elevated correspondingly.

CONCLUSIONS

- The carbon dioxide concentration may be used as an index of the body odor intensity experienced by visitors entering a space with occupants at a given activity and temperature.
- No significant influence of space volume per occupant on body odor intensity or steady-state ventilation requirement was found.
- A relationship between percentage of dissatisfied visitors and CO₂ concentration has been established for sedentary male occupants.

ACKNOWLEDGEMENTS

This study was supported by the Danish Government Fund for Scientific and Industrial Research and the Danish Department of Energy.

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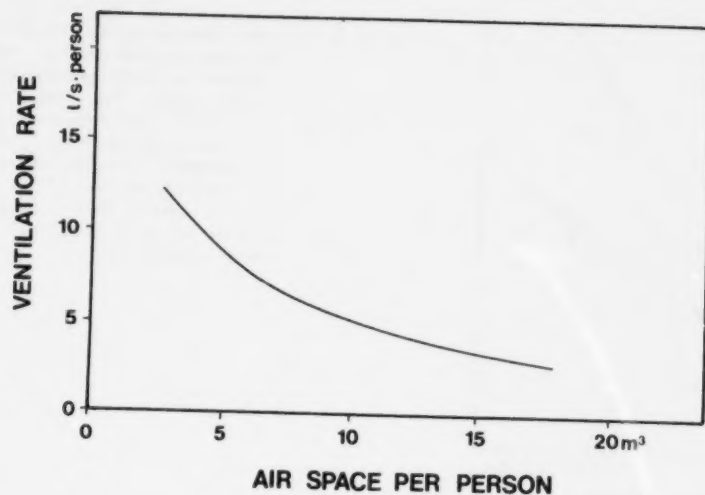


Figure 1. Yaglou's [2] required ventilation rate as a function of air space volume per person. The curve was claimed to correspond to a constant body odor intensity of 2 ('moderate') experienced by visitors

Imagine that you during your daily work should enter this auditorium frequently. Would you judge the odor in the auditorium as acceptable?

acceptable ☐

not acceptable ☐

Figure 2. Question on odor acceptance

How strong is the odor in the auditorium?
Please mark on the scale.

| No odor
 | Slight odor
 | Moderate odor
 | Strong odor
 | Very strong odor
 | Overpowering odor

Figure 3. Yaglou's psycho-physical scale for the subjective judgment of odor intensity (slightly modified). For data analysis these numbers were assigned to the scale: 0 - no odor, 1 - slight odor, 2 - moderate odor, 3 - strong odor, 4 - very strong odor, 5 - overpowering odor

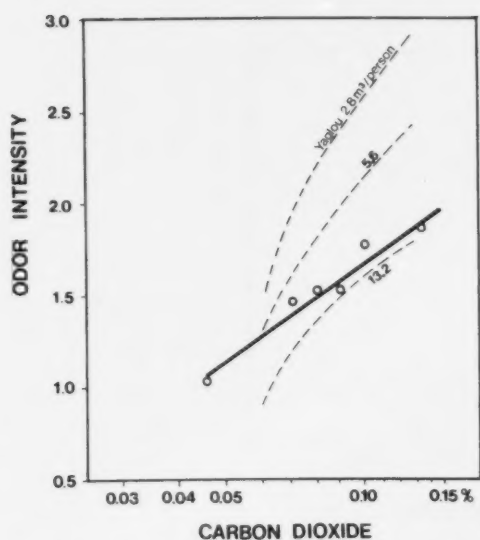


Figure 4. Odor intensity as a function of the carbon dioxide concentration. The points and the regression line are based on the present experiments. For comparison predictions of body odor from a reanalysis of Yaglou's data with estimated CO_2 concentrations are shown. The present experiments showed no significant effect of space volume per person, while Yaglou claimed a strong effect of this factor as indicated by the three dotted curves

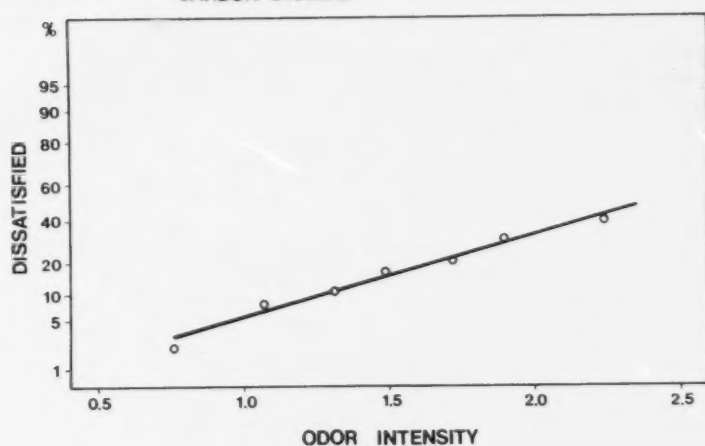


Figure 5. Percentage of dissatisfied as a function of the mean odor intensity

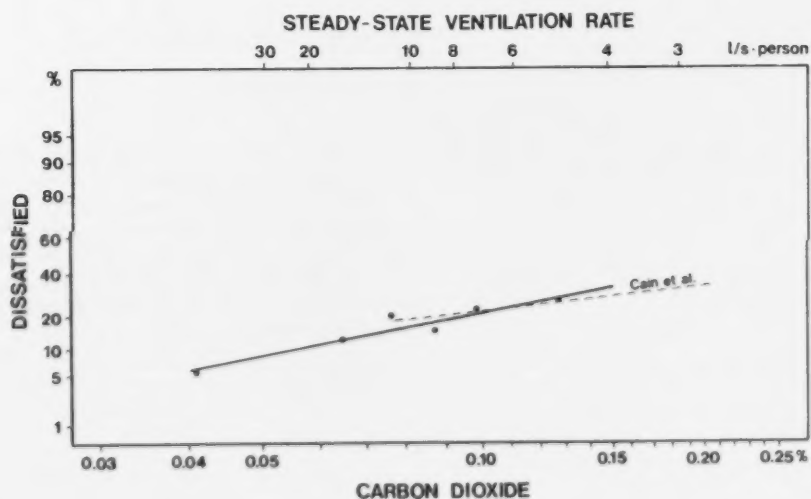


Figure 6. Percentage of dissatisfied as a function of the carbon dioxide concentration

Effect of Ventilation on Passive Smoking Risk in a Model Workplace

J.L. Repace, Ph.D.

ABSTRACT

An estimate of the variation of nonsmokers' lung cancer risk from so-called passive or involuntary smoking is given as a function of ventilation rate in a typical office, at an occupancy of 7 persons/100m² (per 1000 ft²) as specified under ASHRAE Standard 62-1981, Ventilation For Acceptable Indoor Air Quality. Assuming one third of the office workers are smokers who smoke at the average rate of two cigarettes per hour, the nonsmoking office workers exposed to environmental tobacco smoke for a 40-year period under the ventilation rate of 10 LPS/occ (20 CFM/occ) recommended by the standard, would be subject to an estimated lifetime involuntary risk of about 250 per 100,000. This risk is 250 times the maximum lifetime value considered acceptable under commonly used environmental criteria for carcinogenic contaminants in air, water, or food. Practical increases in makeup air or assists by air cleaning, although helpful, cannot reduce the risk to an acceptable level. Decreasing the ventilation rate to the minimum permitted under ASHRAE 62-1981 (2.5 LPS/occ or 5 CFM/occ), common under some building codes, produces a four-fold increase in risk.

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In managing atmosphere in tightly enclosed spaces such as found in mechanically ventilated buildings, ventilation engineers are faced with the difficult problem of determining ventilation rates appropriate to control tobacco smoke to within acceptable levels. Three possible choices present themselves: a standard based upon odor, a standard based upon irritation, and a standard based upon health. Because tobacco smoke has been conclusively demonstrated to be a human carcinogen, and because a number of studies have implicated environmental tobacco smoke in nonsmokers' lung cancer, a health-based ventilation standard for environmental tobacco smoke is the most appropriate. Moreover, "acceptable risk" levels have been defined by agencies concerned with the management of environmental carcinogens, so that the variation of risk with design ventilation rate can be compared with such levels.

In constructing such a standard, it is necessary to formulate the problem in terms of an indoor air pollution transport model based on observable parameters, which can then be varied until an acceptable level of risk obtains. Repace and Lowrey¹ presented such a model in the form of a time-dependent equation for the concentration of tobacco aerosol in a space:

$$A(t) = A_{eq}(1 - e^{-tC_a}) \quad (1),$$

where $A(t)$ is the concentration of the smoke in the room as a function of time, in units of micrograms per cubic meter ($\mu\text{g}/\text{m}^3$), A_{eq} is the concentration of smoke in the room in equilibrium, t is time, and C_a is the effective air exchange rate, which is the sum of the actual ventilation rate C_v , and a rate C_d , due to removal by surface adsorption, multiplied by a ventilation efficiency factor, m .¹ For practical values of C_a , equilibrium will be approached within an hour after onset of smoking. In general, A_{eq} is given by the expression:

$$A_{eq} = n_s r_s E / VC_a \quad (2),$$

where n_s is the number of active smokers, r_s is the number of cigarettes per smoker-hour, E is the emission of sidestream and exhaled mainstream smoke per cigarette, V is the room volume in cubic meters, and C_a is given as before. Expressed in terms of parameters accessible to easy measurement, eq. 2 may be written as:

$$A_{eq} = 650 D_s / C_v \quad (3),$$

where $D_s = n_s / V'$ is the number of burning cigarettes per hundred cubic meters of room space, $V' = V/100$, C_v is ventilation rate, in units of air changes per hour, and 650 is a phenomenologically derived constant. Repace and Lowrey^{1,2} have found eq. 3 to be useful for evaluating field studies of environmental tobacco smoke, and for analyzing controlled experiments. However, for modeling purposes, another variant of this equation is more useful. We define D_{hs} as the habitual smoker density, in units of smokers per hundred cubic meters. D_{hs} is related to D_s by the expression: $r_{hs} D_{hs} = r_s D_s$. For the typical habitual smoker in the U.S., r_{hs} is estimated to be 2 cigarettes per hour (at 10 minutes per cigarette), over a 16 hour smoking day.¹ It is easily seen that for every three habitual smokers, one cigarette is burning constantly, yielding the values $r_s = 6$ cph and hence $D_{hs} = 3D_s$. Thus, for a space occupancy of 9 persons per thousand square feet, with one out of three persons smoking, statistically one cigarette will be observed to be burning constantly. Then, if the number of smokers occupying the space is known -- or can be estimated from the intended occupancy, e.g., the U.S. national smoking prevalence is 1/3 of adults -- A_{eq} can be expressed as:

$$A_{eq} = 217 D_{hs} / C_v \quad (4).$$

The average amount of environmental tobacco smoke inhaled by a nonsmoker in an office is seen to be a function of four factors: the habitual smoker density, D_{hs} , the design ventilation rate, C_v , the respiration rate of the nonsmoker, B_r , which is given in units of cubic meters per hour, and H , the number of hours worked per day averaged over a year. If R_a , in units of lung cancer deaths per year per 100,000 persons exposed, is the maximum acceptable environmental risk level, and if E_r is the exposure-response relationship between inhalation of smoke and lung cancer, we may then determine the maximum permissible daily inhaled exposure, $I_{max} = R_a / E_r$, in units of micrograms/day. B_r may be estimated from tables of respiration rate

for different degrees of human activity. We can calculate X, the maximum ambient tobacco smoke concentration allowable to keep the inhaled exposure less than $I_{\max}$, from the inequality:³

$$X(\mu\text{g}/\text{m}^3) \times B_r (\text{m}^3/\text{hr}) \times H (\text{hrs}/\text{day}) \leq I_{\max} (\mu\text{g}/\text{day}) \quad (5).$$

Solving this inequality for X defines the maximum acceptable concentration in units of micrograms per cubic meter, averaged over an H hour workday, which would be permissible in the workplace to keep the annual lung cancer risk within "acceptable" levels for involuntary risk.

At least five studies have consistently indicated that exposure of nonsmokers to environmental tobacco smoke (so-called passive or involuntary smoking) is associated with lung cancer.⁴ Based on such studies, the exposure-response relationship E_R , has been estimated to be 5 lung cancer deaths per year per 100,000 persons at risk, per milligram daily exposure to tobacco tar, where the population at risk is considered to be nonsmokers aged ≥ 35 years.⁴ The method of estimation is outlined as follows: Repace and Lowrey⁵ estimated the daily probability-weighted average exposure of a typical U.S. adult to be 1.43 mg/day, averaged over mean estimated workplace and domestic passive smoking exposures. Exposure probabilities were estimated from a survey of the smoking policies of 1000 U.S. corporations (both white collar and blue collar; large, medium, and small), and from the percentage of 40,000 children raised in homes with one or more smokers. Hirayama⁶ has reported an annual risk of lung cancer from passive smoking of the order of 7 deaths per year per 100,000 persons at risk. A comparable estimate of the risk of lung cancer of the order of 8 deaths per 100,000 person-years can be derived from a U.S. study of lung cancer in Seventh Day Adventists (SDAs) by Phillips, et al.^{7,8,9}

Albert,¹⁰ has suggested a target risk of 10^{-5} (1 per 100,000) for lifetime involuntary carcinogenic risk to the public. A 10^{-5} lifetime risk is a 1.3×10^{-7} annual risk (assuming a 78-year lifetime). (The U.S. Food and Drug Administration has used a lifetime risk level of 10^{-6} as acceptable, and the U.S. Environmental Protection Agency, in the case of water quality criteria, has used lifetime risks of 10^{-5} to 10^{-7} as acceptable)¹⁰. If we assume a 40-year workplace passive smoking exposure then an acceptable annual workplace risk would be $78/40 \times 1.3 \times 10^{-7} = 2.5 \times 10^{-7}$. Then $I_{\max} = R_a/E_R = 2.5 \times 10^{-7} / (5 \times 10^{-5}) = 5$ micrograms per day.

If we assume an average respiration rate of $B_r = 1 \text{ m}^3/\text{hr}$ (alternate between sitting and light work)¹¹, and an $H = 6$ hour average workday, then $X = 5$ micrograms per day / 6 m^3 per day would be of the order of $1 \mu\text{g}/\text{m}^3$. By comparison, typical ambient tobacco smoke concentrations have been found to range from 100 to 1000 $\mu\text{g}/\text{m}^3$.^{1,2}

We now explore how much ventilation would be required in a typical U.S. workplace to achieve an acceptable passive smoking risk. According to ASHRAE Standard 62-1981¹², a ventilation rate (outdoor air) of 10 L/s per occupant is recommended for office space at a design occupancy of 7 persons per 100 m^2 of floor area (20 cfm per occupant @ 7 persons per 1000 sq.ft.) Assuming a ceiling height of 3 m, and that one-third of the workers smoke¹³, the smoker density is $((7/3)/3.00) = .78$ habitual smokers per 100 m^3 . The design ventilation rate is $70 \text{ L/s} \times 3600 \text{ s/hr} / 1000 \text{ L/m}^3 / 300 \text{ m}^3 = .84$ ach. Thus, in a typical U.S. office, the expected average concentration of tobacco smoke would be (eq. 4) $A_{\text{av}} = 217 \times .78/.84 = 201 \mu\text{g}/\text{m}^3$. (Weber and Fischer¹⁴ reported a mean value within 15% of this figure for 44 Swiss offices chosen at random, implying wider applicability for these calculations). In order to reduce this risk to an acceptable level would require about 226 ach, or 2700 L/s per person (nearly 5400 cfm/occupant), a 270-fold increase in effective ventilation rate, which is completely impractical.

Can air cleaning equipment be a cost-effective substitute for ventilation? A heavy-duty room air cleaner with a fan capacity of 1000 cfm and a 99.97% efficiency HEPA filter cost about \$1800 in 1982.¹⁵ At a unit cost of about \$300/ach, to obtain 226 ach would require a capital expenditure of nearly \$30,000 per smoker, exclusive of operating costs, a clearly uneconomical proposition.

The variation of risk with ventilation rate is given by the following expression, where LCD stands for lung cancer death: $R = A_{eq} B_{HER} = 217 D_{hs}/C_v \mu\text{g}/\text{m}^3 \times 1 \text{ m}^3/\text{hr} \times 6 \text{ average hrs/day} \times 5 \text{ LCDs}/10^5 \text{ person-yrs}/\text{mg}/\text{day} \times 1 \text{ mg}/10^3 \mu\text{g}$, or $R = 6.5 \times 10^{-5} D_{hs}/C_v$ annual risk in units of LCDs per person-year. If we assume a 40-year working career, then the lifetime risk is:

$$R = 2.6 \times 10^{-3} D_{hs}/C_v \text{ LCDs/working lifetime} \quad (6).$$

For the typical office, we take a smoker density of 0.78 habitual smokers per 100 m³ as before, and under ASHRAE 62-1981, a ventilation rate of 0.84 ach, corresponding to 10 LPS/occ. Relative to these conditions, eq. 6 may be rewritten as:

$$R = 2.4 \times 10^{-2} \text{ LCDs}/40 \text{ yr working lifetime per } F_v \text{ LPS/occ} \quad (7).$$

Eq. 7 is used to generate fig. 1, which gives a plot of the lifetime risk, R, in units of lung cancer deaths per thousand workers exposed as a function of F_v , the ventilation air supplied, in units of LPS/occ, over the practical range in ventilation rates.

At the ASHRAE 62-1981 recommended ventilation rate, a nonsmoker's lifetime lung cancer risk from on-the-job passive smoking is estimated to be about 250 per 100,000, far above the acceptable level of 1 per 100,000 for environmental carcinogens in air, water, or food.

It would appear that complete physical separation of smokers and nonsmokers in the workplace or prohibition of workplace smoking are the only feasible alternatives for achieving a health-based standard. Short of this, keeping the ventilation rate in smoking premises as high as possible should be an appropriate goal for design engineers.

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†DISCLAIMER: The views presented are those of the author, and should not be interpreted as official U.S. EPA policy.

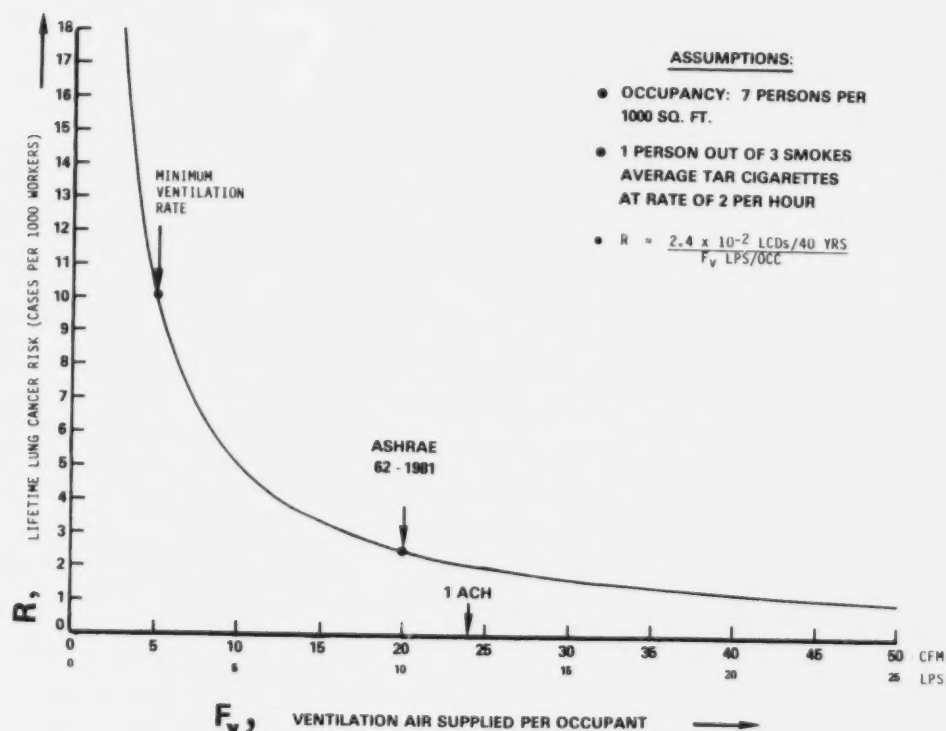


Figure 1. The effect of ventilation on passive smoking in an office setting

The Impact of Building Codes and Regulations on Indoor Air Quality

P.E. McNall, Ph.D.

ABSTRACT

In the United States there is a comprehensive complex and often inconsistent system of regulations which relates to building design, construction and occupancy. These regulations, in the various States, are examined to assess the technical bases for their ventilation provisions and to determine if they permit innovation in indoor air quality technology.

INTRODUCTION

The regulations related to the construction and occupancy of the building itself are the building codes, housing codes, and, in some cases, factory-built or mobile home codes. Ventilation requirements are usually found in the mechanical code provisions. Energy conservation provisions have been added recently, and these often specify the maximum ventilation rates thought to protect health and to reduce energy consumption.

The purpose of this paper is to assess the technical bases for the ventilation provisions and to determine if they permit innovation in indoor air quality technology.

BUILDING CODE DEVELOPMENT

Historically, building regulations were created and enforced to satisfy the objectives of protecting the "health" and "safety" of the building occupants and the public in general. In recent years, a third objective, "welfare," has been added and has received increased emphasis by legislators, code officials, and others writing regulations. Furthermore, during recent years, building codes have become more and more stringent; and new provisions have been added, with very few deletions.

The Constitution of the United States delegates the authority to regulate building design and construction to the States under the provisions reserving police power to the States. In the past, with few exceptions, this authority has been exercised by political jurisdictions at the local level, mostly cities and counties. Recently, there has been a broad movement by the individual States to reclaim authority for the development and implementation of statewide building codes. There are now 35 States that have statewide building codes, in various forms, which are implemented in different ways.¹ Some States offer entirely voluntary use at the local level (Maryland and New York), while others require mandatory usage for the entire State, without amendment (Kentucky, Montana, New Jersey, and Virginia).

Over the years, several national organizations have been formed to improve both the code content and the process for building code enforcement. Three of these organizations are

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associations of building officials; and each promulgates a model building code (i.e., the Building Officials and Code Administrators International (BOCA), the Basic Building Code;² the Southern Building Code Congress International (SBCCI), the Standard Building Code;³ and the International Conference of Building Officials (ICBO), the Uniform Building Code⁴). These model codes are developed and promulgated with the intent that they can be adopted in whole or in part as codes or regulations by appropriate authorities.

The three model building codes cited above are gaining in acceptance and use by State and local governments. Of the 35 States with statewide building codes, 32 are based on either the Basic, Standard, or Uniform model codes. The major cities of the United States also appear to be moving toward the adoption and use of one of the three model codes. The Association of Major City Building Officials (AMCBO), made up of the 31 cities of over 500,000 population, reports that 80 percent of these cities now use the model codes as the bases for their regulations, although many of these cities amended the model.¹ The model building codes are not uniform in format, scope, or content; however, there is a great deal of similarity in scope and technical intent.

VENTILATION AND ENERGY CONSERVATION PROVISIONS IN THE MODEL CODES

The model codes are organized on the bases of building occupancy or use, developed originally for fire safety. They cover one- and two-family residences separately from commercial, industrial and other building uses. Mobile homes are covered separately as well.

Ventilation requirements are found in the code sections on mechanical systems. As energy conservation provisions were added, often ASHRAE 62-73, "Standard for Natural and Mechanical Ventilation,"⁵ was included in the energy conservation provisions, since it is a part of ASHRAE 90-75, "Energy Conservation in New Building Design."⁶ ASHRAE 90-75 is the basis for the model code energy conservation provisions. Therefore, both the mechanical and energy conservation provisions were considered in this study.

Natural ventilation requirements are the only ventilation provisions covered for one- and two-family dwelling codes and mobile home codes. These natural ventilation provisions are prescriptive and specify minimum operable openings. They are originally based on the concept of openable windows when light and ventilation were covered together. Since it is presently impossible to determine the actual ventilation performance of these natural ventilation provisions, they will not be analyzed.

The Basic Model Code, while not specifically referencing ASHRAE 62-73, publishes tables of the minimum ventilation air in cubic feet per minute per human occupant (cfm/person) for various classifications of spaces, which are identical to those in ASHRAE 62-73. In addition, a recirculation option of up to 67 percent is given, provided the recirculated air meets the outdoor air standards of ASHRAE 62-73. No air treatment provisions are included. It also allows 85 percent recirculation, with "effective absorption or filtering equipment" provided the outdoor standards of ASHRAE 62-73 are met. The 5 cfm/person minimum is used, as in ASHRAE 62-73. For practical purposes, the Basic Model Code is equivalent to ASHRAE 62-73 except for allowing the 67 percent recirculation without air treatment. This option, if used, would result in higher indoor levels of internally generated contaminants than ASHRAE 62-73.

The Standard Model Code is not specific on ventilation requirements other than natural ventilation. However, the energy provisions do specify ASHRAE 62-73 as the maximum ventilation rates allowable.

The Uniform Model Code ventilation provisions are summarized below for various use categories or groups. The category definitions are abbreviated, and are for example only.

Group A - assembly category; Group B - 50 persons or less, educational and commercial; Group E - more than 50 persons, educational; and Group H - Storage

- o minimum 5 cfm/person, minimum 15 cfm/person total circulation rate (presumably for mixing)
- o toilets - minimum of 4 air changes per hour
- o natural ventilation openings - 1/10 of floor area, minimum

Group I - Nurseries, Nursing Homes, etc.

- o minimum 5 cfm/person, minimum 15 cfm/person total circulation rate (presumably for mixing)
- o toilets - minimum of 4 air changes per hour
- o natural ventilation openings - 1/20 of floor area, minimum.

Group R - Hotels, Apartment Buildings

- o 2 air changes per hour minimum, 1/5 or more of which shall be outdoor air (assuming 100 ft²/person, outdoor air minimum is approximately 5 cfm/person)
- o natural ventilation openings - 1/20 of floor area, minimum.

If these minimums were applied in practice, the Uniform Model Code would result in significantly higher levels of indoor contamination than ASHRAE 62-73. The energy provisions do specify ASHRAE 62-73 as maximum ventilation rates permissible, however.

The National Conference of States on Building Codes and Standards (NCSBCS) with the model code organizations, BOCA, SBCCI, and ICBO, have produced a Model Energy Code⁷ which is based upon ASHRAE 90-75, including the ASHRAE 62-73 provisions. This has been the basis of the energy provisions in the model codes. The Basic Model Code, however, does not include ventilation in its energy provisions. Several States base their energy codes on the NCSBCS Model Energy Code.

No reference to ASHRAE 62-1981, "Ventilation for Acceptable Air Quality,"⁸ was found in the model codes. ASHRAE 62-1981 is the current standard which replaces 62-73.

VENTILATION PROVISIONS ADOPTED BY THE STATES

Ventilation provisions adopted by the various States, and in some cases municipalities, become the regulatory requirements for buildings in those jurisdictions. Their adoption of ventilation requirements varies. Some adopt one of the model codes without change. Others modify the model codes. Still others write their own codes, but usually base them on some model or other reference document. Some have no code provisions concerning ventilation.

In all cases, of course, larger amounts of ventilation are permitted under the ventilation provisions, if a building designer so chooses. However, the energy conservation provisions generally do not permit larger ventilation rates.

Table 1⁹ summarizes the 1982 status of the 50 States concerning their adopted ventilation and energy conservation provisions for new construction. Table 1 shows that 26 States have adopted, with or without modification, one of the model codes incorporating mechanical code provisions. Nine States have written their own codes, some of which are similar in content to ASHRAE 62-73. Only 15 States have no mechanical code provisions.

Energy conservation provisions for new buildings, using or modifying one of the model codes, have been adopted by 27 States. It has not been determined how many include or reference 62-73, but probably many do. Eighteen States have written their own energy codes. ASHRAE 90-75 was the basis for most, if not all, of these. Only 5 States have no energy conservation codes.

No States have adapted ASHRAE Standard 62-1981 as of this study. In 1980, ASHRAE approved a revision of ASHRAE Standard 90-75, section 1-9, and reissued it as ASHRAE 90A-1980.¹⁰ No States have as yet adapted it in their codes. Since code revisions are a legal process requiring considerable time, it is expected that provisions of both ASHRAE Standards 62-1981 and 90A-1980 will be incorporated in many future code revisions.

CONCLUSIONS

From the brief and incomplete study made here the following conclusions are made:

1. ASHRAE 62-1981 is not yet incorporated in the codes examined.
2. In the codes, minimum ventilation rates in most cases are consistent with ASHRAE 62-73. In some cases the ASHRAE 62-73 minimum rates are specified, and in some the recommended rates of ASHRAE 62-73 are codified as the minimums.
3. The Uniform Model Code permits 5 cfm/person minimum, and therefore its application in practice permits higher levels of indoor air contamination for internally generated pollutants than ASHRAE 62-73.
4. The Basic Model Code 67 percent recirculation option would also permit higher indoor contamination levels than ASHRAE 62-73.
5. Prescriptive rates are specified, and therefore innovative systems which can demonstrate acceptable performance with lower ventilation rates would not be allowed without specific approval of the cognizant bodies, except in the case of the Uniform Model Code.
6. If future research indicates higher rates are necessary for improved indoor air quality, these higher rates would require jurisdictions to change their codes in order to be enforced.
7. Current codes would impede innovations in indoor air quality technologies only if such innovations make possible the use of lower quantities of outdoor air than specified in the codes.
8. The conflicting requirements of energy provisions and indoor air quality are apparent in the codes.

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Table 1
State Code Comparisons⁹

State	Population Ranking 1980	Mechanical Code (usually includes ventilation)	Energy in New Buildings (may include ventilation)
Alabama	22	SBCCI	ASHRAE 90-75
Alaska	50	-	-
Arizona	29	-	-
Arkansas	33	State provisions	State provisions
California	1	ICBO with changes	NCSBCS energy code
Colorado	28	IBCO with change	State provisions
Connecticut	25	BOCA	State provisions
Delaware	47	NFPA 90	ASHRAE 90-75
Florida	7	-	NCSBCS energy code
Georgia	13	State provisions	State provisions
Hawaii	39	-	NCSBCS with changes
Idaho	41	ICBO	ASHRAE 90-75
Illinois	5	-	NCSBCS with changes
Indiana	12	ICBO with changes	State provisions
Iowa	27	ICBO with changes	State provisions
Kansas	32	ICBO	NCSBCS with changes
Kentucky	23	BOCA	-
Louisiana	19	NFPA fire code	NCSBCS energy code
Maine	38	NFPA 31	-
Maryland	18	BOCA	State provisions
Massachusetts	11	BOCA	NCSBCS energy code
Michigan	8	BOCA with changes	State provisions
Minnesota	21	State provisions	ASHRAE 90-75 with changes
Mississippi	31	SBCCI	State provisions
Missouri	15	-	NCSBCS energy code
Montana	44	ICBO with changes	-
Nebraska	35	-	NCSBCS with changes
Nevada	43	ICBO with changes	State provisions
New Hampshire	42	-	State provisions
New Jersey	9	-	ASHRAE 90-75 with changes
New Mexico	37	State provisions	NCSBCS energy code
New York	2	State provisions	NCSBCS energy code
North Carolina	10	State provisions	State provisions
North Dakota	46	-	State provisions
Ohio	6	State Provisions	NCSBCS energy code
Oklahoma	26	-	NCSBCS energy code
Oregon	30	ICBO with changes	NCSBCS energy code
Pennsylvania	4	-	State provisions
Rhode Island	40	BOCA with changes	State provisions
South Carolina	24	SBCCI	NCSBCS with change
South Dakota	45	-	State provisions
Tennessee	17	SBCCI	State provisions
Texas	3	State provisions	NCSBCS energy code
Utah	36	ICBO	ASHRAE 90-75 with changes
Vermont	48	NFPA	NCSBCS with changes
Virginia	14	BOCA with changes	ASHRAE 90-75 (public bldgs only)
Washington	20	ICBO	NCSBCS with changes
West Virginia	34	-	NCSBCS with changes
Wisconsin	16	State provisions	-
Wyoming	49	-	State provisions
			NCSBCS energy code

Substitute Materials

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In recent years there has been a significant increase in the attention given to the indoor air quality issue by the news media and by trade publications. Some sectors of industry have been criticized for creating, knowingly or otherwise, health hazards by exposing housing and building occupants to out-gassing from building materials, soil treatment chemicals, and the like. Some view these criticisms as lacking in appreciation for the complexity of the issue. Others believe there is good cause for concern. The concept of substituting one material for another to avoid creating an indoor air health hazard is one approach to maintaining acceptable indoor air quality.

Many believe that product quality control is the most effective and readily implemented measure with which to abate indoor air quality hazards. In 1980, the U. S. General Accounting Office pointed out the need for adequate material standards and appropriate test methods. Enforcement of the standards would be achieved through testing at the time of production, to control those products which have been identified as sources of indoor air pollutants.

Before deciding to substitute one material for another it is obviously necessary to understand the relative contributions of the two materials to the indoor air environment. Typically this kind of information is conveyed to builders, architects, engineers, interior designers, and specifiers through the nation's system of product and material standards, and the referencing of these standards in building codes and regulations. Thus, in order to know how to select the proper building products and materials so as to avoid contributing to poor indoor air quality, it is necessary to understand the standards development and maintenance processes in the United States.

Although perhaps an over simplification, standards usually are product standards, test standards, or design standards. Typical sources for the majority of these standards are consensus organizations, industry sector associations, independent standards and testing organizations, individual manufacturers, and various levels of government. Some of the more familiar standards writing organizations are ASTM, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the National Fire Protection Association (NFPA), Underwriter's Laboratories, American Plywood Association, the American National Standards Institute (ANSI), and the National Electrical Manufacturers Association (NEMA). There are probably several hundred recognized standards writing organizations serving the building community.

The thousands of active standards are used in several ways. Thousands of private organizational and individual users voluntarily adopt them to meet their needs for compliance with regulations and for procurement purposes. The users include design professionals, building owners, home builders, contractors, manufacturers, insurers, and finance entities. Another way standards are used is through government adoption. Federal agencies such as HUD, CPSC, EPA, DOD, HHS, and DOE routinely write and adopt standards in their guidelines, regulations, and specifications to meet their health, safety, energy, and procurement requirements. These uses are also typical of the 50

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States and the 10,000 or 20,000 local jurisdictions across the country. Another use of standards is through their adoption in quasi-mandatory documents such as model building codes and other standards which are often adopted by government agencies.

The standards development, maintenance, and use processes in the United States are conducted through a myriad of dynamic, fluid programs, sometimes coordinated, most often not. The standards process in the United States, while far from perfect, is envied by and indeed used by many foreign countries. Using product, design, and test standards to effectively, fairly, and quickly achieve improved indoor air quality will require patience, coordination, and a great deal of hard work.

Rising energy costs over the past few years have mandated changes in residential construction standards in order to improve thermal efficiency. In houses, increased insulation and other features to improve the efficiency of the building's thermal envelope have been added, as have more thermally efficient exterior windows and doors, to the point where the intentional introduction of fresh outside air has become the major source of heat loss.

Residential construction standards as late as the 1970's allowed outside air infiltration of at least one change per hour. Many residential forced-air heating systems were equipped with ducted outside air intakes that kept homes under a positive static pressure with preheated air as a technique for controlling drafts. Because of the increased cost of energy, this deliberate introduction of outside fresh air has been virtually discontinued as standard practice by many builders, except where required by code.

Construction standards which minimize air infiltration, together with the use of modern building components such as non-outside exhausting (ductless) kitchen and bathroom ventilation fans, have now been adopted to the extent that many new homes are just short of being hermetically sealed. In homes such as those occupied by the elderly, where little traffic through exterior doors takes place, outside fresh air introduction has been reduced in some cases to less than 0.1 air changes per hour.

In the past, under less stringent air infiltration standards, indoor air contaminants such as nitrous oxide, carbon monoxide, chlordane, radon, ammonia and formaldehyde seldom had the opportunity to accumulate to the extent that occupants even noticed their presence, let alone experienced discomfort or other health effects. With today's tightly constructed homes, the public's concern over indoor air pollution has been aroused to the point that hundreds of lawsuits have been brought against home manufacturers, material producers, and more recently home builders, charging negligence and breach of warranty.

Defense of these claims is often based upon the identification and measurement of individual contaminants and their comparison against attempts to determine safe tolerable levels. There is a lack of definitive and accepted data with which to conclusively determine health effects for many of the suspected indoor air pollutants. From the perspective of the typical homebuilder, and the home buyer, the confusion increases as new contaminants are discovered, prior test procedures are refuted, new measurement techniques adopted, court rulings overturned, formerly accepted data rejected, and so on. It would appear that it will take some time, perhaps many years, for the scientific community to arrive at a set of universally acceptable data, and thus recognized thresholds of contaminants. Until this is accomplished, there remains a public demand for some other procedure to protect their interests. The building industry is in need of reasonable protection from the harassment and financial drain of litigation. At the same time, occupants must be protected from discomfort, illness, or injury due to air contamination.

In addition to suspected and known pollutants entering the home from natural sources, building materials, and appliances, occupants themselves unknowingly introduce additional potential contaminants when they bring such things as furniture, clothing, carpet, drapes, cleaning fluids, and paneling into their homes, or engage in such routine activities as cooking and smoking.

Is the home building industry negligent in their failure to provide homes that maintain indoor air quality that is uncontaminated by pollutants regardless of where, how, or by whom introduced? Over the years procedures have been developed and accepted to protect people from other potential hazards--for instance electrical systems in homes are equipped with automatic circuit breakers that protect the home and the occupant from danger, even in most cases of misuse or abuse. Is it possible to develop these kinds of safeguards to avoid indoor air quality hazards?

In addition to trying to identify, quantify, and establish threshold limits for every known or suspected contaminant (and those not yet identified), reconsideration should be given to such concepts as the introduction of fresh outside air to the extent of one full air change per hour. Some home builders believe the technology now exists to accomplish this, at little penalty in energy efficiency, through the use of heating appliances equipped with heat exchangers which utilize the temperature of the air being exhausted to precondition the incoming air. Wide-spread adoption of this practice would do much to reduce the cost of such equipment and encourage HVAC equipment manufacturers to incorporate this capability into their primary equipment, thereby reducing costs even further.

If such a solution to the indoor air quality problem is of merit, how and by whom might it be furthered within a reasonable time frame? One home builder estimates such a system, based on today's equipment availability and cost, would add approximately \$500 to the cost of a new 1400 sq ft home. With mass production of mechanical equipment which incorporates these features, this cost could be reduced substantially. The builder estimated the energy costs to operate the system to be \$100 per year. Whether or not the cost projections are accurate, it indicates a willingness on the part of some innovative builders to try new problem solving approaches.

Benefit/cost and risk analysis is a good tool for evaluating potential solutions to such problems, but its use is only as valuable as the accuracy of the data used in its application. The lack of these authoritative data is one of the frustrating aspects of the indoor air quality issue. Many want public authorities to take action promptly but some of the "prompt" legislative and regulatory actions taken to date have been challenged successfully due to the absence of a substantive data base. Also, regulatory solutions are usually more costly and less effective than are private initiatives to solve these kinds of problems.

The scientific community has been in the vanguard of the movement to study this issue. More recently other affected interests such as the design professions, product manufacturers, contractors, home builders and building owners have taken an active part in such studies. As these interests begin to question, translate, accept and utilize the scientific findings, solutions in the form of new products, methods and standards will emerge based on new and accepted technology.

In order for this to come about, it is necessary to provide for the early involvement of the affected interests in planning, conducting and evaluating the overall research agenda currently proposed at the Federal level. There is a wealth of research data and professional talent in the building community and it should be tapped. The guidance given by the action of the 98th Congress is a good start in the right direction, but these directions must be pursued to fulfillment.

One effort, to compile at least part of the badly needed data base, is the EPA's Total Exposure Monitoring Program. The indoor air monitoring part of that project will identify actual concentrations of organics, pesticides and inhaleable particulates in the indoor air of four building occupancy types in which large numbers of people spend much of their time. In support of that program, the National Institute of Building Sciences (NIBS), is conducting a fundamental research project entitled, Identification of Building Products and Building Activities to Support Indoor Air Quality Research.

The project is divided into two parts, each with its own objective. The first

is to identify building products, materials, and systems used during the past decade to construct office buildings, schools, homes for the elderly and hospitals. The second part of the study is to identify and categorize primary building operations and occupant activities which may affect the buildings' indoor air quality, and to cite major sources of information for each such activity. Of the building types being studied, the work on office buildings, schools, and homes for the elderly is complete. The part of the study for hospitals has just started.

The purpose for which the findings are to be used was considered in preparation of the format in which to compile the data. It was necessary to present the data in a way understandable to researchers not familiar with building construction and operation. It was also necessary to use techniques by which building materials are traditionally categorized, because much of the available resource material is organized in this form, and those most familiar with the design and construction of these buildings are used to this format. The primary information resources used were technical product literature, generic product listings, building construction contract documents, and the expertise of building design professionals.

Since the materials listing report identifies building products, components, materials and systems by their generic name, the format that was selected builds on the sixteen division building construction specification format developed by the Construction Specifications Institute, also known as CSI. The CSI format is organized in divisions which were originally segregated to facilitate separation of building construction subcontracts. Only fifteen of the sixteen divisions are applicable to this project. They are:

- * Division 02000 Sitework
- * Division 03000 Concrete
- * Division 04000 Masonry
- * Division 05000 Metals
- * Division 06000 Wood and Plastics
- * Division 07000 Thermal and Moisture Protection
- * Division 08000 Doors and Windows
- * Division 09000 Finishes
- * Division 10000 Specialties
- * Division 11000 Equipment
- * Division 12000 Furnishings
- * Division 13000 Special Construction
- * Division 14000 Conveying Systems
- * Division 15000 Mechanical
- * Division 16000 Electrical

The CSI format offers a number of advantages; it facilitates cross referencing; it is the format by which most building construction specifications are organized; and many building material source listings utilize that system. However, if you consider the need to identify the location or use of materials within the building, it is obvious the CSI format alone, is not sufficient. In order to address this need, eleven building elements were selected which represent the major components of a typical building. These elements are:

1. Structure
2. Exterior Enclosure
3. Interior Space Dividers
4. Floorings
5. Ceilings
6. Fixed equipment and Casework
7. Moveable Equipment and Furnishings
8. Vertical Transportation
9. Heating, Ventilating, and Air Conditioning
10. Plumbing
11. Electrical

The fifteen CSI divisions and the eleven elements are combined in the format in which the building products and materials are listed. The format is organized in six columns. The following example illustrates its use:

CSI NO.	GENERIC TYPE	SPECIFIC PRODUCT	COMPONENT MATERIAL	BLDG ELEM	COMMENTS
07220	INSULATION	RIGID BOARD INSULATION	MINERAL FIBER, CELLULAR GLASS, POLYSTYRENE, URETHANE FOAM, PERLITE, FELT	2	ROOFS WALLS
		BATT INSULATION	MINERAL FIBER, GLASS FIBER	2,3	SOUND PROOFING
BUILDING ELEMENTS:					
1.	STRUCTURE		7.	MOVEABLE EQUIP.	FURNISHINGS
2.	EXTERIOR ENCLOSURE		8.	VERTICAL TRANSPORTATION	
3.	INTERIOR SPACE DIVIDERS		9.	HEATING, VENTILATION	AIR COND.
4.	FLOORINGS		10.	PLUMBING	
5.	CEILINGS		11.	ELECTRICAL	
6.	FIXED EQUIP.	CASEWORK			

Approximately twelve-hundred specific products and nearly three-thousand component materials are listed among the three building occupancies studied. As you might expect, the materials listed for each building type were quite similar. The pallet of products and materials available for building construction is generally used for most buildings, no matter the intended occupancy. Products and materials which were found to vary among the three building types generally occur in the categories of: Specialties, Equipment, Furnishings, and Special Construction.

Although the materials report represents a reasonably complete listing of materials used to construct these types of buildings over the last decade, it does not necessarily represent the best or most appropriate materials to be used for such applications. The report is not to be construed as an endorsement of the materials identified.

The material listing can provide data only on some of the variables affecting indoor air quality. Another area believed to have a significant effect on the level of indoor air contaminants is the range of building operation and occupant activities which occur in most buildings. Collection of data in this area is the subject of the second part of the study.

As with the materials report, the building activities listing was separated by occupancy type. The activities were organized into three categories: Construction, Renovation, and Remodeling; Cleaning, Operation, and Maintenance; and Building User Activities. The first part, Construction, Renovation, and Remodeling, breaks the data down into sub categories of design, construction operations, technical standards, general material supply, and data on each of the materials identified in the Materials Listing Report.

The second part, Cleaning, Operation, and Maintenance, includes Cleaning activities such as vacuuming and shampooing carpet, cleaning air filters, and disinfecting fixtures; Operation activities include HVAC, operation of elevators, and sewer and floor drain venting; and the Maintenance listing covers such activities as pest control, repainting, and replacing air filters.

The third part of the activities listing, and the one with the greatest variation among the three occupancy types, identifies user activities. Those activities common to all three building types were listed in one section. They include the personal habits and activities people carry from one area of their environment to another such as; food storage and preparation, smoking, and indoor automobile parking. Activities more typical to each occupancy type were separated in the listing. For instance, the use of office automation equipment and copying machines are more common to office buildings; laundry and hobby activities are most typical in homes for the elderly; and physical education activities and chemistry, physics and biology educational activities are often found in schools.

The activities listing part of the study also identifies major sources of information for each activity. In all, names, addresses, and telephone numbers for three-hundred and twenty-five source organizations were listed by specific activity or material. Within the scope and level of effort of the project it was not possible to determine the exact type, cost, or quality of the information available from the sources listed. However, it is a useful listing of resources for those engaged in these or similar types of indoor air quality research.

The project was made possible and its usefulness was increased because of the thorough and professional work of the Institute's contractor, Pierce Architecture, funding support from the Environmental Protection Agency, the guidance by Dr. Lance Wallace, the EPA's Project Officer, and the advice and valuable technical review provided by the NIBS Indoor Air Quality Subcommittee, chaired by David Ledvinka of The Dow Chemical Company.

The kinds of needed data bases mentioned earlier are being created by the EPA's monitoring program and by the many ongoing research programs of other organizations. As the data are developed, the need for mechanisms to translate and disseminate the information to design professionals, product manufacturers, home builders, public authorities, and others becomes more and more important. This "translation" will eventually take the form of new product standards that address indoor air quality needs and performance-based requirements for other attributes the products and substitute materials must possess. As we pursue our own research projects, it is important to consider how best to translate the findings into new technology, products, standards, and guidelines which will permit others to select correct substitute materials and systems in order to help to avoid creating indoor air quality problems.

Note: although the information described in this paper has been funded in part by the United States Environmental Protection Agency under assistance agreements numbers CR-810519-01-0 and CR-811087-01-0 to the National Institute of Building Sciences, it has not been subjected to the Agency's peer and administrative review and therefore does not necessarily reflect the views of the Agency and no official endorsement should be inferred.

Psychological Factors in the Impacts of Indoor Air Quality on People

J.A. Carlton-Foss, Ph.D.

INTRODUCTION

The effect of the indoor environment on people's health depends on a large number of factors. While in some cases single factors may create a health problem, more often it is two or more factors, often interacting with each other, that are responsible, with no one factor constituting a dangerous condition in and of itself. Manifold technical factors are of central importance to air quality and its effects, but it is my belief that without adequate consideration of psychological factors, and without the integration of rigorous field work efforts with the findings of laboratory studies, it will be impossible to get to the heart of indoor air quality issues. To consider the human dimension properly is not to open a "can of worms" but to reach toward the heart of the matter. In fact, not to consider the human dimension, may well be to create a can of worms. Characterization and consideration of people are essential for valid, reliable research conclusions and for successful application of the findings in design and operations of tightly enclosed spaces (1,2).

The quality of indoor air is of increasing concern to many of us responsible for the indoor environment, for the health and productivity of people, and for the success of organizations. In my experience significant air pollution or thermal discomfort is found in almost every building if a person only looks a little. But often the causes of such problems are elusive and/or have been disregarded by all but the individuals directly affected and the chief building custodian who must field their complaints. This is probably because field work, diagnostic techniques, and orientations commonly used to study indoor air quality have been inadequate. There is much work to be done in sorting out the problems associated with activities in buildings. Thermal gains, office seating and furniture, video display units and software design, lighting design, management-employee relations, individuals' health and personalities, as well as interactions among these and other components, may lead occupants to find fault with the indoor environment. But even as a first approximation, great attention needs to be given to the psychophysiology, psychosomatics, and psychology of human response to indoor air.

These psychological factors contribute as antecedents, concomitants, and consequents of building-associated problems and solutions. When, in the extreme, there is no physical cause for a problem, the symptoms and complaints may under certain further circumstances properly be labelled "psychogenic." However, more commonly, psychological symptoms (e.g., performance losses) may result from exposure to polluted or thermally stressful indoor air. Psychological and physical factors may also interact to yield causes and/or symptoms of a "problem." This integrative perspective is very new and requires major work. Among the components, thermal comfort and its contribution to indoor air quality has been studied and will be discussed first. Then "mass psychogenic illness" or "hysterical contagion," interactive effects, and quantification using psychological measures will also be addressed. References to existing literature will be made, though this paper is intended to focus on the state of the art rather than to review in detail the many established fields that have led to it.

TECHNICAL FACTORS

Some of the most important technical factors that have been recognized include: (1) Thermal climate, described in terms of (a) temperature, (b) relative humidity (rh), and (c) air

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velocity. (2) Atmospheric composition, including (a) gases and vapors normally present in air (N_2 , O_2 , H_2O , etc.); (b) Bioeffluents -- produced by biological processes; (c) Volatile organic compounds (VOCs); (d) Particulate matter; (e) Inorganic gaseous combined products, such as NO , and CO ; (f) Radon, radon progeny, and other radioactive substances that reach the body through the atmosphere; (g) Formaldehyde; (h) Pesticides; (i) Aerosols, particles of organic and inorganic solids and liquids, charged particles (e.g., hydrated ions), or condensation nuclei for viruses and bacteria (including, for example, *Legionella*). (3) "Air distribution," or the "mixing" of ventilation air with air in an occupied space, sometimes measured by the ADPI (Air Diffusion Performance Index which is being addressed by ASHRAE SPC 113P: Room Air Distribution, Method of Testing). All of the species in air may have uniform or non-uniform distributions, and ventilation air may not be efficiently distributed throughout a space unless design and system operation are given due consideration.

On the airplane on my way to this conference, I participated in a nice example of how these technical factors mix with other factors to yield an indoor air quality problem. My plane had been airborne for about a half-hour when I noticed the air becoming foul. I looked forward in my section of the cabin, and noted that several people had lit up cigarettes. The plumes were going straight up, suggesting that there was little or no ventilation. I checked with the people around me, and all were disgruntled about the smoke. Having heard about the recent debate over CAB regulations for ventilation on commercial aircraft, I realized that here was my chance to gain firsthand knowledge of the matter. I checked the supply diffusers, and confirmed that the ventilation was off. I asked the flight attendants about the ventilation; none seemed to be able to tell me where the ventilation supplies and returns were, or whether or not they were operating. When I checked further to make certain that I had not overlooked any supplies, they became aggressively concerned. In negotiations, we arranged for me to talk with a knowledgeable person on the ground. The chief flight attendant asked for my card, and when she saw that I was a professional in the field she became visibly agitated. She went to the cockpit, and about five minutes later the ventilation was on.

This story suggests a number of factors relevant to indoor air quality. One, society is largely ignorant about it. Few people understand what is involved in maintaining satisfactory air quality. Two, many people who are disgruntled about indoor air quality never voice their complaints. Three, it costs money to provide properly conditioned indoor air, and owners and managers may provide resistance instead of clean air. Four, there may be significant interactive effects. In this case the low humidity on board the high altitude commercial aircraft may have contributed to the discomfort caused by tobacco smoke (3). These observations presumably apply not only to airplanes, but also to buildings.

The history of concern with indoor air pollution is illustrative. It was in the late 1970s that the number of complaints became really significant. It seems that, in part, people had become alerted to the problems of chemical and other pollutants in their environments (5), and that indoor air quality problems had been exacerbated by an increased tendency to minimize energy costs by reducing ventilation (6). There was also increased use of automated office equipment and an aging of the workforce, both of which may require more favorable environments than have traditionally been thought necessary in offices (7, 8). It was also in the late 1970s that the Emergency Building Temperature Restrictions (EBTR) came into effect. These were formulated to avoid significant health problems, not to maintain occupants' comfort or productivity, and certainly not to minimize complaints. Work in thermal comfort and acceptability suggests that warm discomfort is likely to be a significant component in complaints about indoor air quality, that there is an identifiable pattern of individual differences in peoples' responses, and that major parts of the methodological approach of thermal comfort research can be (or in some cases, already have been) carried over to studies of the impacts of pollutants on indoor air acceptability.

THERMAL COMFORT

Human response to thermal environments has traditionally been studied as a function of eight variables: (1) dry-bulb temperature, (2) mean radiant temperature, (3) water vapor pressure, (4) air velocity, (5) clothing level, (6) activity level, (7) time, and, occasionally, (8) heat storage in the body tissues. In principle, these are all objective, measurable statistics. Models of thermal acceptability and comfort have used them as parameters and have offered an impressive, albeit approximate, description of environmental conditions for human comfort.

Fanger's (9) physiologically-based, environmental engineering theory of thermal comfort models the human body in much the same way that an engineer models a building. Both the

building and the body have an outer surface through which heat is gained or lost. The amount of heat transfer for given internal and environmental conditions depends upon the total surface area and insulation-value of the surface. Both building and body surfaces are permeable to heat transfer, the magnitude and direction of which depend on internal and environmental variables. For example, the rate of conductive heat flow varies linearly with the temperature difference between the interior and the exterior. Additional factors are mean sol air temperature (for buildings) and mean radiant temperature (for people), the velocity of air in the environment, the water vapor pressure in the environment, and the amount of heat gained internally. Fanger presents explicit equations for internal heat generation, heat loss by skin diffusion, heat loss by evaporation of sweat, latent respiration heat loss, dry respiration heat loss, heat conduction through clothing, heat loss by radiation, heat loss by convection, and heat balance, that is, the equation that must be satisfied in cases where the body is in thermodynamic equilibrium. On the average, the closer bodies are to thermal equilibrium, the more comfortable people are presumed to be.

Judgements of the comfort and/or acceptability of thermal environments have been scored on ballots with a one-dimensional scale, or a seven-dimensional semantic differential scale. Subjects are given a sheet of paper with the scale on it, and asked to indicate their evaluation of the environment. An environment is regarded as "acceptable" if at least 80% indicate that it is "comfortable." This approach has also been used to set standards for current work on comfort-based acceptance of odors and of indoor air quality in general. Figure 1 and Figure 2 present samples of the traditional one-dimensional ballot (10) and the seven-dimensional ballot developed by Rohles (11,12)

Subjects' responses to each of the scales are multiplied by a weighting factor, the products summed, and the sum divided by a normalization constant to yield the percent comfort rating (with 100% being perfectly comfortable). This approach is important for developing the next generation of evaluations of pollutant-modified indoor air quality because it acknowledges the varying words (i.e. concepts) people have for describing different aspects of their environments.

We have found, however, that even such an improved scale is not enough to capture an accurate report of people's comfort or discomfort. In addition, information must be gathered on the adaptation level of a subject (13), that is, on what environmental conditions subjects prefer and what words they use to describe those conditions. In thermal comfort research the issue is whether the subject regards "warm" as "good," or "cool" as "good." The importance of such information became obvious when a subject circled "8" (= hot) on a one-dimensional ballot and then wrote on the ballot: "I like it that way." Adaptation level and personality became key dimensions in the research reported below on individual differences in environmental response.

INDIVIDUAL DIFFERENCES

Considering its simple assumptions about the nature of people, Fanger's theory does a good job of explaining the average thermal responses of large populations as long as they are comfortable or nearly so. However, individual differences and psychological factors in thermal comfort (14,15) must also be addressed. We have found that, for example, low rather than high anxiety and the degree to which people are the origins of their relation with their environments are correlated with a broader "bandwidth" of environmental conditions that people will find acceptable. (Note: I did not say "prefer" at the end of this sentence.) In other words, people who are "origins," will tend to be more adaptable than pawns.

There were three independently measured variables in a field study testing this theory. "Self-definition" measured a respondent's position in the origin-pawn dimension of personality. Frederick Rohles' "comfort index" measured respondents' percent satisfaction with the thermal environment. "Corrected temperature" was a measure of the temperature in an environment after variations in relative humidity, clothing and activity level were normalized to a preselected standard. "Corrected temperature" differs from "effective temperature" only in being normalized to 40% relative humidity. These three measured variables are plotted on the graph in Figure 3, each point corresponding to one respondent. The vertical axis is self-definition [origins corresponding to + numbers toward the top of the scale and pawns to - numbers at the bottom of the scale]; the horizontal axis is corrected temperature. Contours have been drawn around groupings of thermal comfort scores to assist in visualizing the shapes of the scatter plots for those reporting relative thermal comfort (the Rohles semantic differential comfort index greater than 50%) and for those reporting relative thermal discomfort (the Rohles comfort index less than 50%). Of the 41 people in the sample, 29 had a

comfort index score greater than 50%. Two of the people provided data that did not fall within either contour; both of them were tested at home during the evening after work, while all the rest were tested in public places.

Correlations between personality and comfort were significant at the 0.02 level and origin-pawn accounted for 15% to 20% of the variance in comfort of people who were acceptably comfortable, and for 30% to 37% of the comfort level of those who were uncomfortable.

There is a crucial point underlying these data and this analysis. If no attention is given to individual differences and their source, the data indicates only that there is a scatter of points about a central temperature. There are no significant correlations, and we cannot even distinguish those who are thermally uncomfortable from those who are thermally comfortable. However, when attention is given to subjects' thermal sensation adaptation level and to their personalities, we do get a temperature dependence, and we can begin to distinguish those who are uncomfortable from those who are comfortable (15). Theoretical work in this area (16) indicates several additional psychological variables which could be used to develop even better models for such individual differences.

TOWARD CRITERIA FOR MASS HYSTERIA

One of the major problems of work with complaints of "stuffiness" or "poor indoor air quality" is the tendency to discount the psychological domain and credit only measurable physico-chemical sources of illness in buildings so that when nothing specific can be identified as "the cause" of complaints, problems are often labelled "psychogenic." This ends up in a logical doublethink because people are first eliminated from consideration, and then blamed when the technical analysis doesn't yield a cause. There is a tendency to treat as "psychological" that which cannot be measured or understood. This gives psychologists a bad name among technical people, and technical people a bad name among psychologists. In fact, we should all be working together.

Just that no specific physical causes have been identified is not enough evidence to conclude that there is "hysterical contagion" in a building. Instead, we must look to see if the pattern of those with symptoms correlates with the pattern of susceptible personality types, and if the pattern of symptom-free people correlates with that of people of low susceptibility to such contagion. It is also necessary to find out if those with complaints and pathologies are not simply more aware, sensitive, exposed, and/or able to make themselves heard than the others.

It is possible to list specific criteria for susceptibility to hysterical contagion. These can help to distinguish between those highly susceptible to psychogenic disease, and those highly unsusceptible to it. Criteria include: (1) demanding dependency rather than mutuality; (2) vague, impressionistic perception of the environment and the self; (3) use of repression as a defense mechanism; (4) poor logic, or spotty reliance on logic in reaching contact with reality; using hunches as if they were reality; (5) incapacity for persistent or intense concentration (17,18). Items 1, 2, 4, and 5 are similar to the "pawn" personality, while their opposites approximate the "origin" personality (19,20). These characteristics are quantitatively and objectively measurable, and can be used to inform studies of complaints and syndromes in the field.

An preliminary test of this theory is offered by a study we performed in a 50,000 sq. ft. building in the greater Boston area. We were brought in because there were extensive complaints of "stuffiness" in the computer and personnel departments. We performed detailed measurements of environmental conditions, and distributed questionnaires to the occupants using exactly the same method as in our earlier work on thermal comfort (21,22,23). Air velocities were well under 10 feet/minute, a condition in part resulting from high open office partitions and attempts to reduce ventilation to save energy. Temperatures varied from 70½°F in the computer room to 81°F in a clerical area of the personnel department (see Figure 4). However, the occupants' evaluations of their environment did not correlate with environmental conditions. Instead, they correlated with personality. While temperature and other environmental variables accounted for less than 1% altogether, occupants' scores along the origin-pawn dimension accounted for 41% of the variance in evaluations of the environment: origins were significantly less satisfied with the indoor atmosphere than were pawns. Since the environment was in fact "stuffy," we concluded that the origins had been perceiving their environment accurately, and were doing something rather more constructive than merely "gripping" or manifesting hysterical symptoms in relation to their indoor environment.

STRESS AND REACTIONS TO ENVIRONMENTS

The psychodynamic theory of stress, disease, and health provides an underlying model for responses to indoor atmospheres. [Readers who are involved with engineering and not interested in clinical issues may wish to skip to the next section.] Selye (24) posits that stressors internal and external to the organism impinge upon it, creating ever higher levels of stress. In a broad sense, any event requiring adaptation or assimilation is stressful, though it should be kept in mind that reasonable total stress levels may be desirable. Low temperature is one example of an environmental stressor (25). Poor air quality is another, as are many other factors related to the senses as well as to the mind and body. Stress is dissipated by the organism, but might not be dissipated as rapidly as it is accumulated. Once the stress reaches a certain threshold, the organism begins to malfunction. This "disease" may take various forms, e.g., undesirable behavior, performance deficits, medical illness, death. Common to all such "diseases" is the general stress reaction, the "general adaptation syndrome." Part of this syndrome, stimulation of the sympathetic nervous system resulting in vasoconstriction in the extremities and piloerection (26), is readily interpreted as cold discomfort. In fact it can lead to physiological cooling of the extremities, and to other symptoms of arousal, all of which individuals will be inclined to interpret in one way or another. More generally, Schachter (27) has reported on work indicating that people may interpret internal sensations associated with arousal in any one of a variety of ways, depending on their inclinations and the demand characteristics of their environment. Frank (28) states this succinctly when he writes that Schachter "showed that persons who are physiologically aroused are impelled to search for a reason and that the emotion they actually experience seems to be a fusion of the state of arousal with the person's attribution of its source." This suggests that there will be individual differences in peoples' responses to the environment: some people will be more inclined to interpret their internal sensations (of whatever cause) as discomfort or illness than will others, and some people will be more likely to attribute that discomfort or illness to environmental factors than will others.

Individuals under stress develop adaptive and maladaptive functioning in stages. The details of the function and dysfunction depend upon individuals' ego organization (29,30). Many predictive hypotheses can be derived from this psychodynamic theory, though it is also extremely important to emphasize that people untrained in psychology must not be permitted to give facile diagnoses of "personal problems" as a means of avoiding mitigation of real air quality problems. If people use somatization as a defense at a given level of stress, they might tend to become physically sick in response to sufficient stress. (Note that this stress is the accumulated stress of internal and external origin from activities in all sites that a person has recently frequented.) If they use passive-aggressive defenses, they might tend to complain behind the back of the person who controls the environment. If they use displacement, they might think the office is cold or polluted when actually they are angry with their supervisor. If they use denial, they may invest extreme energies in maintaining their exposure to substances that will harm them, meanwhile denying (without awareness, and sometimes with apparent aplomb) that these substances are really harmful to themselves or to anyone else. If they use sublimation (i.e., this may mean that they are highly motivated), they might tend to work harder and to be more productive until pollutants yield significant detrimental effects. If they are accustomed to taking effective, constructive action to cope with and find remedies for problems, they might tend to do the same in the face of environmental stressors.

The impact of the stress due to mild environmental discomfort may be small in most cases, but it is not difficult to imagine a 5% shift toward the use of less mature patterns of thought and behavior. Such a shift in situations in which more mature styles are required can have considerable impacts on delicately balanced personal and social systems (see 31). It should also be recognized that there will be cases in which apparently mild stress increments will lead to major regression, or (particularly for people under medication) even to death (32,33,34,35,36).

TIGHT BUILDING SYNDROME: THERMAL CAUSES?

How then can we measure and diagnose these problem conditions? How can we formulate and carry out laboratory research that is relevant (i.e. is valid and has high external reliability)? Considering the technical and psychological factors involved, the work is hardly straightforward, and even highly skilled specialists will necessarily find it a considerable challenge. Clearly, we must be very sophisticated in how we ask subjects or people in buildings about their environmental responses. Most of these people cannot deduce the causes of their responses to their environments. They experience sensations which they interpret on the basis of personal beliefs, personality, or interests, influenced by the situational cues

including the interpersonal ambience in the workplace or laboratory. One "building associated epidemic" seems to have been triggered by a new odor which appeared in the office after a long period of smoldering discontent about the indoor environment (37). Experimenter-subject effects (e.g., positive and negative Hawthorne effects and placebo effects) are well known, but seem to have been addressed primarily by Rohles (38) and Carlton-Foss (39).

In order for investigators to determine what remedies might actually be useful, they must determine the real problems in a building. Complaints of "poor air quality," "lack of air motion," "stuffiness," or other subjectively evaluated conditions must be investigated on several fronts: airborne contamination, thermal conditions, engineering and architectural issues, and personal and organizational dimensions. Some investigators have put considerable effort into measuring the composition of the air with complex equipment, while some have not even recorded temperatures. Some investigators have given out extensive but unfocused and unreliable sociological questionnaires to gather the opinions of building occupants, but have acquired little useful personal or organizational data (40). A few relatively skillful investigators have serendipitously discovered hidden causes of air quality complaints such as improper construction or operations, a simmering labor-management problem, and disgruntlement about uncomfortable temperatures (40,41).

But people in normal buildings probably should be complaining about "stuffiness" (42). Interior zones are cooled all year. In many variable volume (VAV) system operations, thermostats in the interior of a large building are satisfied by heat migration from the interior to the perimeter. Thus VAV in interior zones will operate at minimum volume for most of the time and ventilation will be inadequate.

In addition, it is unlikely that enough moisture will be removed from interior spaces. Thermostats typically used in buildings sense only the temperature and not the high humidity levels that are often created by occupants, plants, equipment, and weather. At these humidity levels, people not only require lower temperatures for comfort, but also are apt to be more aware of odor problems.

Air movement is also important. Of course, partitions and acoustical panels can obstruct air motion, but air diffusion technologies are also an issue. Air diffusion systems at volumes of 0.6 CFM/ft² (cubic feet ventilation air per square foot of floor space) and velocities of 20 FPM (feet per minute) can maintain temperatures within $\pm 0.3^\circ\text{F}$ throughout a space. However, no known air diffusion system can maintain uniform air motion between 25-45 FPM, the air speed required to meet the requirements of ASHRAE 62-1981 for comfort at 78°F and 1.0 CLO (43).

Consistent with Int-Hout's work, Bruce Findlay (44) reports that most air quality complaints in his Canadian government buildings have been resolved simply by adjusting the thermostat by a few degrees. He found, for example, that the costs are not always great for changes from 77°F to 72°F during the summer. He reports only a \$1000 increase in summer cooling costs for a 22,000 m² modern office building (with an economizer cycle) in Ontario, and much reduction in complaints. This offers anecdotal corroborating evidence for the "hot-air" hypothesis, though unfortunately, there is no research yet begun on the subject.

QUANTIFYING COMFORT AND HEALTH EFFECTS

In general, building owners and managers have tended to use complaints as an index of the acceptability of environmental quality. This is risky because complaints are often a biased, discontinuous measure of environmental quality, and there may be a serious medical situation by the time a real problem is acknowledged. In contrast, ASHRAE has focused on comfort when comfort factors are more sensitive than documented health effects as the primary criterion for acceptable [indoor] air quality. The notion of comfort has been based on people's votes on scales similar to the thermal comfort scales. Using the comfort-vote technique, there is, for example, a threshold of acceptability at about 0.1 ppm for formaldehyde in indoor air (45) whereas 1.0 ppm is OSHA's standard for medical danger for people in the workplace. Such comfort-type scales have also been applied to research on comfort and acceptability of odors in occupied spaces.

Comfort and odor evaluations may, however, not always provide adequate measures of risk for an airborne substance. People become accustomed to odors and certain other non-thermal cues, so that for example, a smoker will often be less sensitive to the effects of smoke concentrations than will a nonsmoker. Further, there are individual physiological differences in people's response to odors, so that some people might find diesel fumes objectionable

because they are more sensitive to the "pungent-acid" odor component, while others may find it pleasant because they are more sensitive to the "aldehyde-aromatic" component. Further, people may differ in their notions of whether the same odor is pleasant or noxious. This highlights the need for objective measures of indoor air quality particularly when air pollutants are evaluated as pleasant rather than noxious.

There are two types of such measurement: (a) performance effects and subclinical symptomatology, and (b) medical symptomatology, morbidity and mortality. Psychological and subclinical medical symptomatology may be the first signs of, for example, carbon disulfide poisoning: Victims may initially experience headache, dizziness, increasing sense of weariness, loss of strength, transient excitement, and slight delirium very like alcoholic intoxication, followed by deep depression and loss of memory, increasing indifference and apathy. This might change suddenly to acute mania or delusions of persecution with hallucinations, ending with recovery or incurable dementia. As late as 1946, psychiatrists were admitting victims of carbon disulfide poisoning to mental hospitals with comments such as "etiology occupational" or "unknown" and no reference to carbon disulfide (46). Since many of these symptoms may also occur for other reasons in everyday life, meticulous differential diagnosis in research efforts and in industrial hygiene in the field is required. In addition, performance effects may be the first and most significant clues of pollution in normal living circumstances. For example, Weiss (47) writes that the carboxy-hemoglobin levels in the blood of heavy smokers may reach levels of 5% to 7% or greater, and that this is near the threshold for impaired vigilance performance. If Weiss' view is confirmed, the implications could be considerable for heavy-smoking motorists in congested traffic. These, and better substantiated performance effects and subclinical symptoms often show up earlier than acute medical ones, and in some cases can provide precise, sensitive measures of the impacts of environmental pollutants.

Studying the performance and subclinical effects of noxious chemicals could lead into serious ethical problems unless an on-site example happened to be found and exposure levels could be accurately estimated. However, this same psychological methodology can be demonstrated as applied to chairs by a recent study we did (48). Chairs, like air quality and temperature, can be considered as one of many possible environmental stressors producing both general and specific effects. The basic idea behind the study was that ergonomically sound chairs would reduce physiological stress as well as cognitive loading on users, who would therefore perform better than those who used "standard" office chairs. Thus, we sought to measure the non-specific impacts of stress associated with use of higher quality versus lower quality chairs (analogous to the general impacts of toxic substances). Similar designs could be used to measure the specific effects of various other environmental stressors.

Two groups of experienced typists were seated for a full day at the same workstation, but with different chairs, to learn a standard word processing program and then to use it to enter pre-typed originals into the computer. Questionnaires were administered before and after the work session to measure additional psychological variables. Five operators using an ergonomically sound office chair were compared with six operators (controls) using a standard office chair. Those in the ergonomic chair learned the software 20% faster, reached a 13% higher performance plateau, and maintained performance levels 40% higher during the final 1½ hours of the 5½-hour trial period (see Figure 5). It seems that the poor equipment reduced the performance of the controls, and I expect that studies of the impacts of many low dosages of environmental pollutants on people's performance of complex tasks will show a similar pattern.

Thus, psychological methods can be used to measure effects that are extremely important to organizational decision makers, though they may have no immediate medical impact on people.

Of course, at higher or more prolonged levels of exposure to toxic substances or probably even to low quality furniture, there will be less subtle symptoms -- sometimes acute medical symptoms and even a higher death rate. Spengler's group (49,50) for example, has determined that children growing up in homes with at least one parent a smoker have 5% to 25% higher well-to-risk ratios than do children growing up in non-smoking homes. Tobacco smoke and other airborne contaminants have also been found to be significant contributors to fatal disease. An epidemiological study of death rates of male British doctors over 20 years, for example, showed that smokers had a death rate (standardized for age) due to chronic respiratory illness about 16 times that of non-smokers (51).

A more continuous measure of the effects of pollution on people is provided by dose-response curves. These curves represent the impacts of varying exposures to an [airborne] toxic substance or combination of such substances. Traditionally such curves have been drawn

with respect to severe symptomatology and death, but performance deficits and other more subtle measures could also be used to establish relationships at the low-dose end of the curve. Such measures eventually must be correlated with more severe symptomatology in longitudinal studies. What we have now is primarily documentation of these symptoms once they require medical attention. In the British doctor study, for example, it was found that the annual death rate for chronic bronchitis and emphysema per 100,000 men was 3 for non-smokers, 38 for those who smoked 1-14 g/day of any tobacco, 50 for those who smoked 15-24 g/day, and 88 for those who smoked 25 or more g/day. These numbers were plotted, and a curve fitted and tested using the chi-square distribution. Using such a technique it is in principle possible to determine the level of risk (in terms of types of illness per capita or deaths per capita) for any given exposure to a toxic substance. Of course, individual differences (including those associated with psychological factors) may again complicate this approach. For example, Type AA people (as genetically determined) metabolize benzo (a) pyrene into the carcinogenic material, aryl hydrocarbon hydroxylase, ten times as much as people who are not Type AA (52,53). Thus people who are Type AA might be exposed to a much greater health risk than non-Type AA people even though both were functioning in the same indoor environment. Behavioral differences, leading one smoker or non-smoker to be exposed to more smoke than another would result in additional differences. However, the most significant area of contention about dose-response curves is how they should be extrapolated from high to low levels of exposure. To the extent that such questions can be resolved for various pollutants, dose-response curves could be useful. In this way psychological and medical measures can be used along with comfort and odor-acceptability measures to inform decisions about what constitutes an "acceptable" environment for people.

CONCLUSION

This paper has presented theory and work that I believe is very important for resolving issues of acceptable conditions for indoor environments. A correct approach to indoor environmental quality must, I believe, be very thorough, incorporating many of the areas discussed above in addition to the traditional epidemiological and hygiene areas. This increases the complexity of the task, but it also offers us the chance of more complete resolution of the issues of comfort, health, and performance. Work taking the multitude of factors into consideration must be done. The simplistic solutions all-too-commonly offered in practice to complex problems may yield quick fixes in a small but seductive fraction of cases, but when they lead people to avoid the struggle of thoughtful, focused analysis of situations, they must be decried. It is for people like ourselves to work together as colleagues in our various disciplines to get to the heart of indoor air quality issues for occupied spaces.

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Vote No. _____ Test No. _____

Number _____ Sex _____ Name _____

Circle the number beside the adjective
that describes how you feel.

9	Very Hot
8	Hot
7	Warm
6	Slightly Warm
5	Neutral
4	Slightly Cool
3	Cool
2	Cold
1	Very Cold

Figure 1. One dimensional thermal comfort ballot

Thermal Comfort Ballot

According to the instructions, place a check between each pair of adjectives at the location that best describes how you feel:

comfortable	_____	uncomfortable
bad temperature	_____	good temperature
pleasant	_____	unpleasant
cool	_____	warm
unacceptable	_____	acceptable
uncomfortable temperature	_____	comfortable temperature
satisfied	_____	dissatisfied

Figure 2. Rohles' seven dimensional thermal comfort ballot

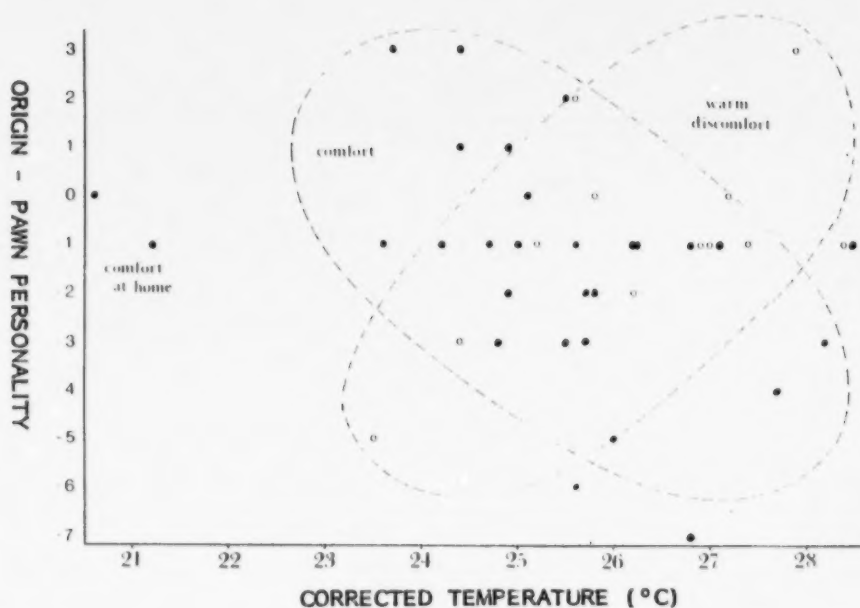


Figure 3. Thermal comfort, origin-pawn, and corrected temperature. The scatter plot above represents data points for the research. The vertical position of a point represents the origin-pawn score for a subject (origins at the top or [+] end of the scale, pawns at the bottom or [-] end of the scale). The horizontal position of a point represents the corrected temperature for a subject. The solid dots represent subjects who reported thermal comfort (RCI) greater than 50%, while the open circles represent subjects who reported thermal comfort no greater than 50%. The oval labelled "comfort" highlights the approximate envelope of the data points for people reporting thermal comfort in organizational settings. The oval labelled "warm discomfort" highlights the approximate envelope of the data points for people reporting too warm in organizational settings. The points to the left of both ovals are labelled "comfort at home," signifying that they reported thermal comfort greater than 50% while at home. This suggests that such variables as anxiety and "feeling at home" are significant factors in comfort and discomfort.

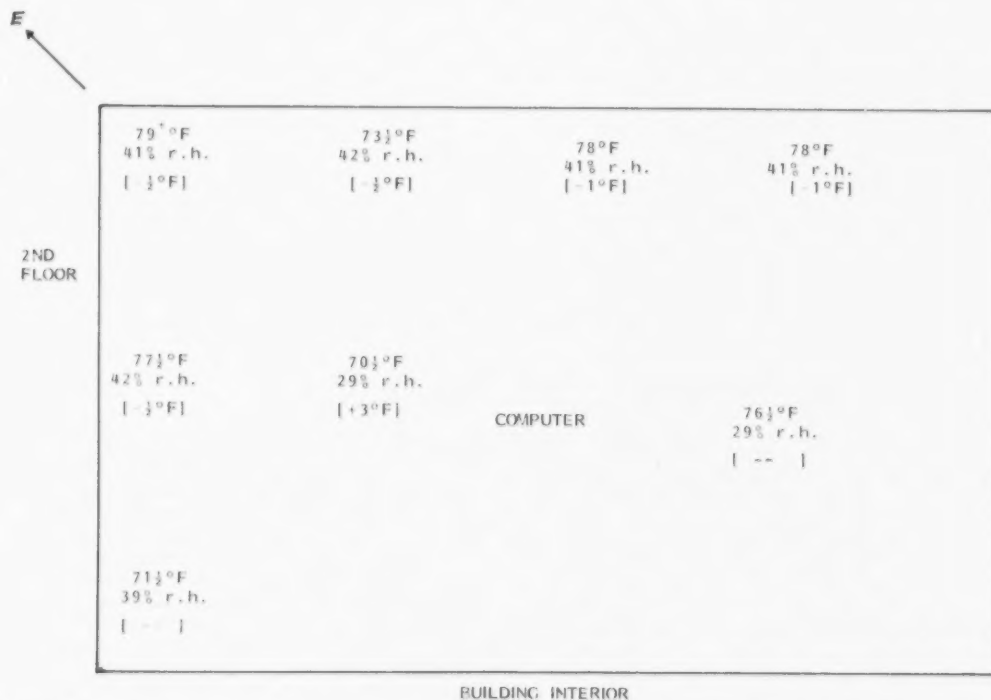


Figure 4. Distribution of dry bulb temperature and relative humidity in a 50,000 square foot office area in which there were complaints of "stale air."

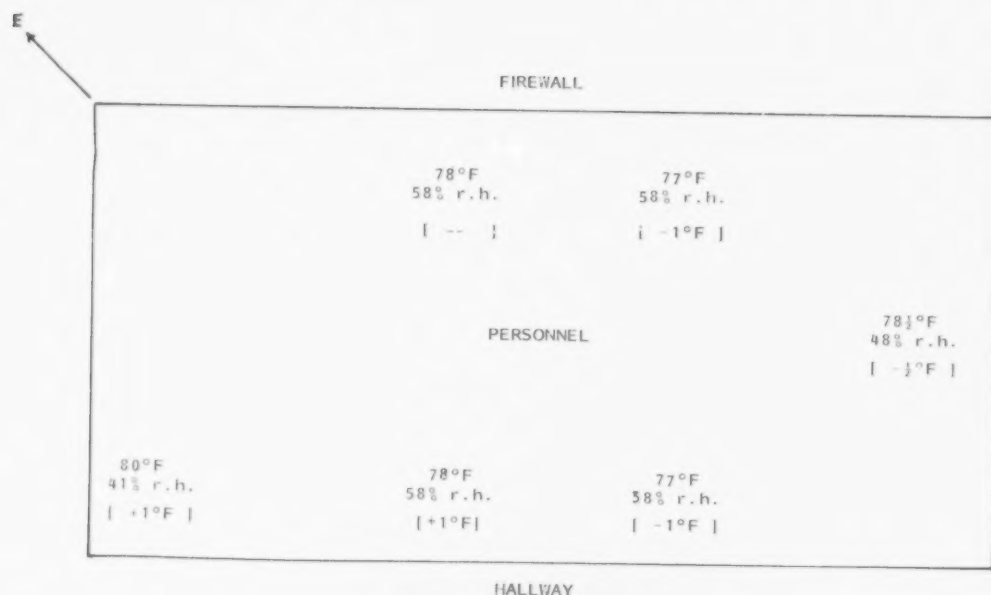


Figure 4. (continued)

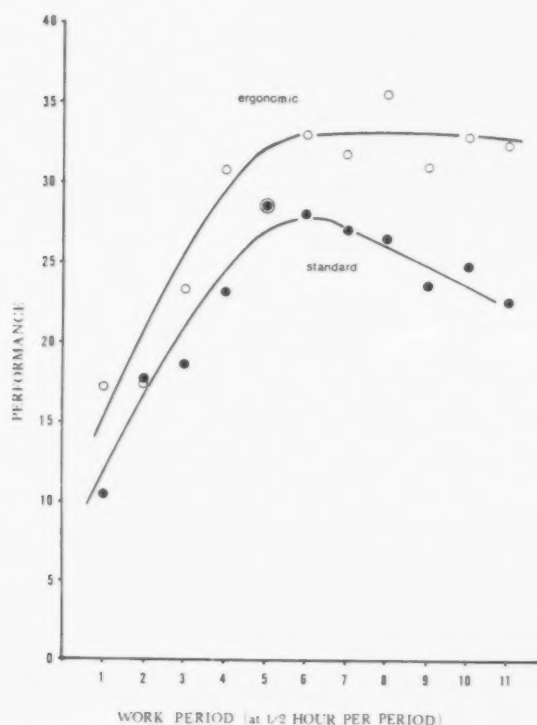


Figure 5. Performance at a word processing task as a function of time and chair used. The first part of the graphs are learning curves with the same coefficients and different time constants. The time constant for people using "ergonomic" seating was 20% shorter than for people using "standard seating." The constant coefficient in front of the learning curve exponential function is approximately the same for both curves, indicating that the observed differences between groups is not the result of different typing abilities. Once subjects had learned the word processing task but had lost their freshness, their performance leveled off. In the resulting plateau region in the middle of the day, people using "ergonomic" seating performed 13% better than those using "standard" seating. In the final time periods, people using maladjusted "standard" chairs became fatigued and their performance dropped significantly. During this final 1½-hour period, people using "ergonomic" seating performed 40% better than those using "standard" seating. All these results were statistically significant.

Radon Concentrates and Ventilation Rates in Eastern Pennsylvania Houses

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INTRODUCTION

The distribution of radon in houses is an important issue for both public health and energy conservation, making it crucial that the factors governing the distribution of radon in houses be discovered and understood through careful analysis.

The amount of radon daughter exposure is proportional to the rate of excess lung cancer development in uranium miners (Beir, 1980), and most workers feel that environmental exposures account for a large fraction of the lung cancer observed in nonsmokers. Because environmental exposures usually have been at low dose rates, there is divergence among authorities on the appropriate extrapolations from miner data to environmental risk. Published estimates range from 100 to 1,000 lung cancers per million working level months of radon daughter exposure (Table 1). Martell (1983) suggests further that much lung cancer among smokers also involves radon daughters causally.

Determining the distribution of exposure for large populations would be feasible with available passive monitors but has not been carried out. Instead, based upon the observation that most people spend 80-90 percent of their time indoors, investigators have chosen to measure concentrations in buildings, particularly houses.

The most striking characteristic of the distribution of radon concentrations is its extremely wide dispersal, typically two or three orders of magnitude within a region and more between regions. As stressed by Sachs and others (1982), the lognormal distribution typical of these studies implies control by a number of factors interacting multiplicatively. That analysis of variability stressed that geologically controlled variables (soil, soil permeability, water supply) would exhibit this great variability, while other potential contributors (ventilation rate, building materials) usually show less variability.

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If geological variables govern the distribution of those areas in which high values are likely, such areas should exhibit the spatial coherence (on a scale of 1-100 km) characteristic of most geological outcrop belts and most aquifers (which supply subterranean water).

It is well-established that ground water can be a major source of radon in houses (Hess et al., 1979, 1980). It is also well-established that trends of high radon concentration in houses are sometimes correlated with geological features. Hess et al. (1979) noted the association of high radon concentrations with location on granites and high-grade metamorphic rocks in Maine, a relationship that is expected to hold for much of northern New England and probably for other regions as well. Sachs et al. (1982) stressed the strong association of high concentrations with specific sedimentary rock "belts" in eastern Pennsylvania. Statistically, location is an important variable in predicting radon concentrations for these houses (Gross and Sachs, 1982).

In contrast, neither building materials nor ventilation variability appears to account adequately for the broad distribution of radon concentrations in houses. As reviewed in several articles in the Third Natural Radiation Environment and in Nero and Lowder (eds, 1983), building materials generally a narrow range of emanation variability.

Ventilation is best considered as a modulator or amplifier of an underlying source, since it has a fairly narrow distribution, with most houses apparently having long-term ventilation rates between 0.5 and 1.5 air changes per hour (ACH), (Nero, 1983). For some hypothetical steady radon source strength, a decrease in ventilation rate will increase the concentration of radon in a dwelling; this relationship has been demonstrated in an instrumented house. Among energy-efficient houses, there seems to be a general inverse relationship between ventilation rates and radon concentrations, but the data are quite scattered (Nero et al., 1983). Indeed, LBL data for 99 houses of various construction styles show no simple relationship between radon concentration and ventilation rate.

With this background, our goals in this prototype study were clear: We wanted to specify as many components of the radon budgets of conventional houses as possible, to examine the magnitude of the contributing factors. We chose a representative panel of 37 houses in eastern Pennsylvania. Each house was located with respect to its geological formation (the underlying substrate) by Sachs and A. van Assendelft. Harrje and Gadsby coordinated and took responsibility for the blower-door ventilation measurements by Princeton personnel. Prichard analyzed the concentration of radon in the domestic water supplies from samples gathered by Sachs and Gadsby. Prichard also arranged for the use of Terradex Track-Etch (R) Type F passive radon detectors (Alter and Fleischer, 1981). Field difficulties in deploying the detectors in frozen ground prevented large-scale radon concentration study.

METHODS

The time-varying concentration of radon in a house is given by

$$\frac{dN}{dt} = S + \frac{N_a}{T_a} - \left[\frac{N(t)}{T_r} + \frac{N(t)}{T_a} \right]$$

where N is concentration, S is source strength, N_a is the outdoor (ambient) concentration, T_a is the ventilation constant of the building, and T_r is the mean life of a radon-222 atom.

This equation is valid for the extreme situation in which the structure can be treated as comprising only a single, well-mixed chamber. In real houses, radon concentrations in basements are often two to ten times higher than in living areas above the basement (e.g., Sachs and others, 1981; Table 2 of this paper), so that the one-chamber approximation is not completely appropriate. Nonetheless, even in these cases one can consider the living area to be modeled by a single-chamber situation. The 2-chamber situation has been investigated by Hernandez and Ring (1982).

Steady-state conditions are not reached in houses of conventional design. Among other factors, barometric pressure gradients can cause short-term but large-scale variation of the source strength (Hernandez, et al., in pres). The ventilation rate of conventional houses is also a strongly varying function of indoor-outdoor temperature gradients and the local wind field (Persily, 1982).

On the other hand, we are interested in exposure, which will be linked to long-term average concentrations. For this reason, the use of long-term integrating monitors of radon concentration is most appropriate, and it is important to select ventilation measurement methods that can approximate long-term average ventilation rates as well.

The goal of approximating long-term ventilation measurements led us to choose blower-door pressurization methods to approximate ventilation rates instead of using tracer gas dilution methods. It is generally accepted that the tracer gas systems are more accurate, but of limited applicability until integrating monitors become more widely available (Dietz et al., 1983). Short-term tracer gas methods yield information only on instantaneous ventilation rates, except where expensive continuous monitors are employed. This is prohibitive for large field studies.

In contrast, the blower door methods measure the flow of air induced by a calibrated door-mounted fan as a function of the pressure difference between the inside (affected by the fan) and the outside (Blomsterberg and Harrje, 1979). The pressurization or depressurization profile, in conjunction with knowledge of the house volume and flow rates can be used to determine a tightness value at 50 pascal (pa) or an Effective Leakage Area (ELA) at 4 pa differential pressure for the building. From this, the ventilation rate can be approximated (Sherman and Grimsrud, 1980). Alternatively, a useful empirical relationship is that the seasonal average ventilation rate is strongly linked to the 50 pascal pressure difference flow rate divided by 20 (Persily, 1982; Kronvall, 1978). In this study, we have used both the Effective Leakage Area values and the Princeton approximation, respectively labeled as LBL and PK ACH on Table 2.

As noted above, all radon measurements for air were made with Terradex Track-Etch type F integrating passive monitors, exposed for at least two months. These devices were placed in the houses by the occupants, and generally were picked up by Princeton staff at the time the ventilation measurements were made for each house.

15 mL water samples were collected by Princeton field personnel at the time of blower door measurements. In each case, water was drawn into a plastic syringe from a cold-water tap running freely. The water was then injected under 10 mL of scintillator in a 25 mL scintillation flask. Duplicate samples were taken for each location. All houses served by private wells were sampled; only representative samples were taken in houses served by the same community water supply. Analysis by Prichard followed the alpha scintillation methods of Prichard and Gesell (1977).

Because we do not expect large-scale temporal variability in radon concentrations of water supplies, and because all water supplies in this region that have been measured have had concentrations no higher than 20,000 picocuries per liter (pCi/L), we feel that this sampling strategy served the project needs adequately.

As indicated above, the location of each house was interpolated on the largest scale available geological map to determine the underlying substrate; this approach led to very specific assignments in almost every case. This system led to the recognition of 11 different geological categories largely equivalent to those of van Assendelft and Sachs (1982). This is too many for analysis of a data set of this size. In addition, the relative frequencies were very highly skewed, with two categories having 10 houses each, and no other categories having more than three houses. Consequently, we clustered the geological variables into four categories: Group 1, All Great Valley formations, a group dominated by the Leithsville and Allentown rocks; Group 3, comprising houses on the Mauch Chunk Formation; Group 4, houses on the Marcellus; and Group 5, all others of Silurian to Triassic age. Our original Group 2, Beekmantown of the Great Valley, was combined with Category 1 because there were only two Beekmantown houses. [There were no houses located on igneous or metamorphic rocks in this study.

Participants in this study were all uncompensated volunteers. In the Allentown and Bethlehem region, participants were recruited from the members of the Geology Department, Lehigh University, and their friends. We also studied houses in two much smaller towns, referred to as "C" and "D" in this report. In each of these towns, the volunteers were members of the faculty of local schools or their friends. In this report, information that might lead to the identification of these participants has been aliased to preserve confidentiality. In each case, the relevant location and contact data for each house are recorded at the Center for Energy and Environmental Studies, Princeton University. A duplicate file is maintained by the senior author.

RESULTS

As noted above, the potential "supply" terms in the radon budget are the local geological conditions (soil, soil permeability, substrate), the building materials, and the supply water. The "sink" is limited to dilution by ventilation and a much smaller (ca. 100x) elimination by radioactive decay.

We elected not to study the emanation of radon from building materials, either in situ or in the laboratory, for three reasons: (1) This study was designed to be as unintrusive as possible. (2) There were severe restrictions on available manpower. (3) There have been no indications of building material problems in prior studies in the region.

In this report, we will first address the findings by variable, and then consider the results for computed variables and variable interrelationships.

1. RADON IN AIR. Data for thirty houses are given in Table 1 and summarized in Table 3. Several characteristics of the data set require comment. First, the logarithmic average concentration in the living areas is 4.7 pCi/L, an uncommonly high value. The corresponding cellar logarithmic average is 6.5 pCi/L. Clearly, the data for new houses (less than 10-15 years old) are quite distinct from those for the older houses. For 16 older houses, the living area and cellar concentrations had logarithmic averages of 2.9 and 4.0 pCi/L, respectively, while the 12 newer houses had

comparable values of 10.6 and 13.7 pCi/L. These values are comparable to those found by Gross and Sachs (1982) in an analysis of the 36-house Pennsylvania Power and Light cohort analyzed by Sachs and others (1983). The implications for human exposure in the future are discussed below.

The living area radon concentrations were almost always lower than those in the cellar in this study. Of 30 houses with complete radon data, cellar values were lower in only 8 (27%). As shown in Table 3, in six of these cases, the values were very close (within 1 s.d.); the two remaining cases are marginally further separated.

We infer from this pattern that the predominant sources throughout the region are in the basement. Important living area sources (much greater than cellar sources) would be marked by living area concentrations consistently higher than those in the basements (this is strictly true only if the volumes and ventilation rates are comparable). This implies that the local geology is likely to be a strong control element. We also infer that water is at best an infrequent major source of radon in these houses (see also the discussion below) and that building materials used upstairs (e.g., gypsum drywall board) are relatively unimportant as well.

2. RADON IN WATER. The study included 15 houses served by private wells; the average radon concentration for water drawn from these supplies was 1550 pCi/L, (935 to 2540 pCi/L, 1 s.d., arithmetic average concentration). It is clear that conventional houses have enough ventilation and interior volume that no likely water use pattern will allow water at these concentrations to be a significant source.
3. VENTILATION RATES. As noted in the Methods section, we have computed two different ventilation indices, referred to on the ventilation summary table (Table 4) as LBL and PK. The LBL index is the air change rate calculated from the equivalent leakage area, which in turn is computed from the pressurization profile. The PK value is based on the empirical relationship of dividing the flow (ACH) at 50 pascal depressurization by the constant value 20.

Overall, the LBL figures indicate that the houses are more well-ventilated than the PK estimates (by 32%, a value that is significant). Thus, it is clear that the two indicators are not equivalent. However, they are highly correlated, with a Pearson correlation coefficient of 0.84 ($p < 0.001$).

The data set comprises roughly two-thirds older (greater than 10-15 years) and one-third newer houses, and it is interesting to compare the two data sets (Table 4). First, by either of the two measures, the younger houses are much tighter than the older ones. Air change rates for the older ones are 1.7-2.0 times higher than for the newer houses in this panel. As important, the younger houses show much less variability in their ventilation rates, as measured by the 1 standard deviation errors given on Table 4. On average, the variability of the ventilation rate of the newer houses is half that of the older ones. We infer from this that since the 1973 oil crisis builders have learned to construct houses that are much tighter than the old average, which included some rather tight and many rather leaky houses.

4. SOURCE STRENGTH. Estimated source strengths for each of 26 houses have been computed from the computed ventilation rates, integrated living area radon concentrations, and measured house volumes (determined by Princeton field personnel while doing blower-door determinations). The data are presented in Table 2.

As noted above, two different ventilation measures are available, the PK and LBL estimates. Both are presented in Table 2. We have chosen to work with the simpler PK approach to air change estimates in the succeeding comparisons.

5. THE CONTROLS OF RADON CONCENTRATION. The "General Linear Model" of the Statistical Analysis System (SAS, 1979) was used to predict radon concentrations from the measured variables of Table 2. In separate runs, the radon concentration in the living area and in the cellar (both logarithmic and linear) was estimated from combinations of variables including the radon in the water supply, house age (old vs. young), the LBL and PK air change values, the LBL and PK computed source strengths, geology, and the number of floors in the house. In these analyses, continuous variables (e.g., radon in water) are treated as independent variables in a regression, while classification and dichotomous variables are included in a form equivalent to analysis of variance. Classification variables like geology can take several distinct states which cannot be ordered. Dichotomous variables can have one of only two possible values.

As indicated in Table 5, the computed relationships between the dependent variables (radon concentrations) and the independent variables (location, age, etc.) were all highly significant. The general linear models account for over 80% of the variance, or information, of the data set. Unfortunately, the data set is very small, since only 22 houses had complete information, and thus no single component stands out as a significant contributor to the regressions. This contrasts with the results of Gross and Sachs, who found a very strong "location" (geology) signal in their analysis of a somewhat larger data set from the same region.

DISCUSSION

This study can only be considered as a small pilot program to demonstrate that effective methods are available to examine the variables controlling radon distribution in large groups of houses. From the high fraction of the variance accounted for (greater than 80%), we believe that we have measured most of the important variables in this region, or linearly correlated "proxies" for them.

Despite its very small size, this study has again shown the strong association of a particular suite or group of sedimentary rocks with elevated radon concentrations. Because these and similar rocks are very widespread, we believe that this conclusion is extremely significant.

With a much larger study, it will be possible to identify specific formations within the region that are strongly associated with high radon concentrations, and begin the process of rational control of radon through revisions of the building codes to assure that radon is precluded from houses or can be readily eliminated where found.

Because radon concentrations in the living area were almost always lower than in cellars, we believe that it is unlikely that living area materials (e.g., drywall) are significant contributors of radon in this region. It is possible that basement materials, such as the concrete, do contribute;

this remains to be measured. However, it is unlikely that this material will be found to be a significant source (Ingersoll 1983). Unless there was a change in the source of concrete about 10 years ago throughout the region, there is another reason to doubt that the concrete used in this region is a particularly strong source: Almost all the older houses show relatively low radon concentrations, in the range seen in other regions.

Indeed, the role of ventilation in this region is very large. We have seen (Table 4) that the older houses are much more leaky than the newer ones, and that their leakiness is much more variable. We stress that the houses in this study are entirely conventional; none were designed as solar or energy-efficient buildings. On average, the older houses had about double the air change rates of the newer ones, and the variability from house to house was twice as great.

The inferences from this are clear: Since energy prices began to escalate, builders have responded by a variety of measures designed to improve energy efficiency, including additional insulation and careful weatherstripping. This led to significant decreases in natural infiltration. Still, only 3 of the 12 newer houses with ventilation data had PK ventilation rate estimates lower than the tightest of the old houses. Most of the change has been in making all houses as tight as the best of the old houses, rather than in the introduction of measures that would allow houses to be made extremely tight (Elmroth and Levin, 1983).

Source strengths tend to fall into two discrete groups. Houses with high radon concentrations (greater than 10 pCi/L) have source strengths in excess of 3 microcuries per hour, while those with radon concentrations less than 4 pCi/L have low radon source strengths. Clearly, in a larger data set there would be a continuous gradation in source strength values, but this type of data exploration is essential to begin searching for regions and conditions that favor high radon accumulations.

The data set from eastern Pennsylvania, fewer than 75 houses studied to date, is too small for strong health and policy inferences. However, it is very suggestive of strong health implications. Because the average radon values in the newer houses are so high (greater than 10 pCi/L logarithmic average winter values in two data sets), we would expect an increase in the lung cancer over the next few decades. However, because the latency period of lung cancer induced by radon exposure is long (decades) and the dose rate in the newer houses is still fairly small in most houses, we do not expect a lung cancer "signal" in the present death rate data for the region. Simply put, it will not be until after the turn of the century that enough people will have lived long enough in post-1970 housing for an epidemic of excess lung cancer to begin.

Because so few other regions have been adequately studied, we do not know where else similar patterns will be found. We do feel that it is imperative that we begin to work now to assure that exposures in this region are controlled, that similar regions are identified, and that we learn to avoid radon contamination in houses.

SUMMARY AND CONCLUSIONS

1. This pilot study of 37 houses has confirmed that the sedimentary strata of eastern Pennsylvania have the potential to support significant amounts of excess radon in houses. Values in excess of 80 pCi/L were found in conventional houses. Our data convince us that the radon in these houses arises largely from the soil and is introduced into the houses through their foundations.

2. Newer houses have more radon, experience lower ventilation rates, and show less ventilation variability from house to house than the older houses in this study.
3. It is unlikely that the excess radon is caused by contributions from building materials.
4. No single house in this study had high enough radon concentrations in its water supply to account for more than a small fraction of the radon in the house; peak values were less than 5000 pCi/L. On the other hand, at least one municipal water supply, at 1600 pCi/L, might be thought by conservative authorities to pose some additional risk to the population using it.
5. If this problem is not addressed, and if the BEIR (1980) estimates are correct, then we expect to begin to see excess lung cancer due to radon exposure after the beginning of the twenty-first century. Until then, there will not have been enough population-years of exposure, since the older houses in this region have relatively low radon concentrations.
6. Because the radon is introduced through the foundations, relatively simple engineering changes and precautions at the time of construction should suffice to assure that radon can be controlled without sacrificing energy efficiency. In affected areas, the appropriate requirements should be added to the building codes as soon as feasible, and occupancy should be contingent on satisfying a radon concentration criterion.

Acknowledgements

The initial impetus for this study was provided by the opportunity to analyze data generated by the Pennsylvania Power and Light Company. We are grateful to Dr. A. George for introducing us to the problem. Field ventilation studies were supported by U.S. Department of Energy; Building Systems, Conservation and Renewable Energy, Contract DE-AC02-77CSZ0062. R. Crosby and D. Jacobson assisted in data generation and analysis, Dr. D. Strawn provided SAS analytical assistance. Track-Etch (R) radon detectors were provided by Mr. Mike O'Connell of the Office of Radiation Programs of the US EPA. Dr. R. Oswald compiled Table 1.

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Table 1
LUNG CANCER RISK ESTIMATES
(compiled by R. Oswald)

UNSCEAR, 1977	$200-450/(10^6 \times \text{WLM})$	"United Nations Scientific Committee on the Effects of Atomic Radiation, 1977" Report to the General Assembly, Annexes, G&B (United Nations, New York, 1977).
BEIR, 1980	$10-50/(10^6 \times \text{person year} \times \text{WLM})$	BEIR Report "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation" 372-397 (National Academy of Sciences, National Research Council, Washington D.C. 1980).
EVANS, 1981	$100/(10^6 \times \text{WLM})$	EVANS, R.D., Marley, J.H., Jacobi, W., McLean, A.S., Mills, W.A., Stewart, C.G. "Estimate of Risk From Environmental Exposure to Radon-222 and its Decay Products" <u>Nature</u> 290, March 12, 1981.
JACOBI, 1979	$100-500/(10^6 \times \text{WLM})$	JACOBI, W. "Proceedings of NEA Specialist Meeting on Personal Dosimetry and Area Monitoring Suitable for Radon and Daughter Products" Paris, 223-230 (Nuclear Energy Agency, OECD, Paris, 1979).
ARCHER, 1979	$1000/10^6 \times \text{WLM})$	ARCHER, V.E. Trans. Am. Nucl. Soc. 33, 145-145-146 (1979).
MEYERS & STUART	$21-54/(10^6 \times \text{WLM})$	MEYERS, D.K. & Stewart, C.G., AECL 5970 (Chalk River Nuclear Laboratories, 1979).

Table 2

House Identi- fication	Radon Concentrations			House Age 1= >younger 0= >older	Calculated Air Changes/hr		Geological Class	No. of Floors	1-Chamber Calculated Source Strength, microcuries per hour
	Living area	Air	Water		LBL (ELA)	(PK)			
A4	1.2	2.7	10	.	1.56	1.03	1	2	1
A6	1.8	4.1	10	.	1.04	0.63	.	2	1
A9	.	.	.	.	1.65	1.07	1	1	1
A2	2.2	2.0	10	0	0.92	0.58	1	2	1
A7	5.1	4.7	10	0	.	.	1	.	.
B1	3.0	5.6	540	0	1.09	0.73	1	2	4
B3	7.4	7.4	1740	0	1.82	0.84	1	2	2
C2	4.1	6.8	10	0	0.58	0.51	.	2	2
C3	5.9	3.8	4600	0	1.25	0.89	5	2	4
C4	6.0	14.8	1900	0	1.45	1.06	3	2	4
C5	2.8	8.9	2485	0	0.97	0.89	3	2	6
C6	0.8	2.6	1045	0	1.17	0.41	3	2	5
C8	5.0	7.8	1955	0	1.02	0.67	3	2	1
L4	2.8	0.8	65	0	1.63	1.05	3	1	1
L5	0.5	1.9	10	0	1.59	1.06	5	2	5
L8	1.9	3.0	65	0	0.89	1.10	5	2	3
L9	1.6	4.4	65	0	1.38	1.60	5	2	1
L10	6.5	8.9	65	0	1.18	0.90	5	2	3
A1	32.4	55.1	945	0	.	.	5	2	1
A3	7.1	11.4	1375	1	0.46	0.34	1	1	11
A5	3.2	4.2	10	1	0.58	0.44	.	2	3
A8	7.9	10.4	10	1	0.93	0.71	1	2	2
B2	1.2	2.5	10	1	0.84	0.69	1	1	5
C1	16.0	43.0	1640	1	0.76	0.52	1	2	1.
C7	7.5	6.2	1400	1	0.82	0.44	3	2	7.
L1	84.0	113.0	1990	1	0.74	0.42	3	2	3.
L2	13.1	12.4	1355	1	0.48	0.39	4	1	33.
L3	1.6	0.5	65	1	0.45	0.28	4	2	4.
L6	80.0	204.0	2215	1	1.16	.	5	2	54.
L7	17.3	16.6	955	1	0.79	0.67	4	1	.

TABLE 3
SUMMARY OF RADON DATA

		Radon in Air, pCi/L					
		M	Living Area		Outer Cellar		
			Geometric Mean	1 s.d. span	Geometric Mean	1 s.d. span	
I.	All houses studied	30	4.6	1.4-15.8	6.5	1.7-24.8	
II.	Houses <10-15 yr old	12	10.6	2.7- 4.0	13.7	3 -73	
III.	Houses >10-15 yr old	16	2.9	1.3- 6.2	4.0	1.8-9.1	

TABLE 4
SUMMARY OF VENTILATION DATA

		Variable	Mean	Error Estimate (+1 s.d.)	Sample Size
I. All data					
		LBL air Change rate	1.10	+0.59	32
		PK air change rate	0.83	+0.53	33
II. Older houses (age > 10-15 years)					
		LBL air Change rate	1.27	+0.68	18
		PK air change rate	0.99	+0.60	
III. Newer houses					
		LBL air Change rate	0.73	+0.22	11
		PK air change rate	0.49	+0.15	10

Table 5

Dependent (predicted) Variable:	<u>Living area</u>		<u>Cellar</u>	
	<u>Linear</u>	<u>Logarithm of Radon</u>	<u>Linear</u>	<u>Logarithm of Radon</u>
% Variance accounted for by pre- diction	95%	82%	98%	86%
Probability >F (all highly significant)	0.0001	0.0027	0.0001	0.0006

Independent variables included radon in water supply (linear and logarithmic transform values), house age class (dichotomous), air change rate estimates (LRL and PN), geology (classes 1,3,4, or 5), 1-chamber source strength estimates (based on LRL and PN estimates), and the number of floors in the house. Data for 22 houses are included.

Electronic Air Cleaners and the Indoor Environment

B. Krafthefer

ABSTRACT

The growing awareness over the quality of air in the indoor environment is driving the search for effective control methods for the contaminants of concern. Electronic air cleaners can control such pollutants as dust, pollen, tobacco smoke, radon decay products, and other particulates. This paper presents an examination of the various types of electronic air cleaners and their effects on indoor pollutants. It also examines the mechanism for contaminant removal, the relationship of the efficiency to the characteristics of the contaminant, and what type of contaminants can be controlled with the electronic air cleaner, with particular emphasis placed on the removal of radon decay products. From a study on radon product removal in residences, the electronic air cleaner was found to have an efficiency of up to 70%. Not only was there a reduction in the residential working level, but the fluctuations in the working level were also reduced. With this information, We can better understand how to solve the air treatment problem of the inhabited space.

INTRODUCTION

From studies being conducted in the characterization of indoor contaminants, it is being recognized that some means must be found to control these contaminants. Several control methods are being investigated, including source removal, source dilution, general ventilation, and filtration. Each of these methods has its advantages and disadvantages.

The filtration method considered in this paper is the electrostatic method of filtration, usually called an electronic air cleaner when used for cleaning recirculated air and when used in indoor environments such as residences and small commercial applications. An examination will be made of the type of contaminants this device can remove; the mechanism of removal; the dependency of removal efficiency on both particle and air cleaner characteristics; and the air cleaner as a control in a particular environment and its effects on the particular contaminant of radon decay products.

Some of the contaminants found indoors^(1,2,3,4) on which the electronic air cleaner can be used are tobacco smoke, the particulate phase of combustion products, consumer products such as pesticides and aerosols, asbestos, radioactive dusts, sulfates and nitrates, and biological particles such as pollen, microbes (which could be molds, bacteria, fungi or mites), and the particulates associated with human occupancy of the environment such as hair and skin flakes.

The size range of particulates found indoors is quite extensive, ranging from⁽⁵⁾ below 0.01 micron for air ions, radon products, and viruses, to up above 100 microns for pollens and spores, as shown in Figure 1.

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Not only is there a wide range of particle diameters, but there is an equally wide range of concentrations depending on source strength, geographical location, and meteorological parameters such as temperature, wind speed, and time of day. The sources for particles found indoors may be inside sources such as smoking, unvented combustion appliances, and use of consumer products; or the sources may be outside for contaminants such as sulfates. The concentrations can range from 10^5 - 10^8 particles/cm³ for tobacco smoke⁽⁶⁾, 200-20,000 microbes/m³ for bacteria⁽¹⁾, or ~0 to over 48 fibers/L for asbestos⁽⁷⁾. Measurements for the respirable fraction with smokers present can range to 700 μ g/m³⁽⁸⁾.

Figure 2 shows measurements made at locations in the United States, Canada and in Europe of radon decay product concentrations that have been measured in residences. The range of radon decay product activity extends from below .001 WL to upwards of .7 WL found in some earth sheltered energy conserving residences^(9,10,11).

The concern over particulates in indoor environments is with esthetics (such as wall staining over cooking ranges), with comfort, and with the health problems that may arise from the inhalation of these contaminants and their deposition in the respiratory system. Particles larger than 15 microns will usually be filtered out by the nasal cavity, but open mouth breathing can bring these particles into the bronchial airway. The efficiency of deposition, as shown in Figure 3 by the ICRP model⁽¹²⁾, of particles in the respiratory system approaches a minimum between 0.1 and 1.0 microns and then increases for smaller sizes which are deposited into the alveolar area in the pulmonary region. The mechanism of deposition is by impingement in the bronchial airways and by diffusion in the alveolar region.

Concern over the inhalation of particles is not only due to the accumulation of dust in the lungs, but is also due to the health effects of biological particles. These can be harmful effects even at very low concentrations. In case of the ragweed spore, only one spore may be harmful⁽¹³⁾. Infection can be caused by only 1 tuberculosis spore in every 500 m³⁽¹⁴⁾. Also radioactive dusts, such as radon decay products, can produce radioactive "hot-spots" in the lung tissue that may eventually lead to possible cancer.

BACKGROUND ON ELECTRONIC AIR CLEANER

There are essentially three types of electronic air cleaners, as shown in Figure 4: the two stage ionizing-type, the charged-media nonionizing type, and the charged media ionizing type⁽¹⁵⁾.

The two-stage ionizing-type of air cleaner generates positive ions by means of a corona in the first stage. These ions then move across the air stream striking and adhering to any dust particles. These particles then pass into the second stage which consists of a series of charged and grounded plates. The charged particles will then have a component of their velocity along the electric field lines and will travel toward the plates where they are collected.

The charged-media nonionizing air cleaner combines the characteristics of both dry filters and electronic air cleaners. It consists of a dielectric filter medium, usually arranged in pleats supported by a gridwork consisting of alternately charged and grounded members, the charged members usually being held at 12 kV d.c. An intense, non-uniform field is thus created in the dielectric medium and the airborne particles are then polarized and entrapped in the filaments of the media. The resistance to flow of this device increases as the media loads with particles and is serviced by replacing the filter medium. The dielectric properties of the media are impaired when the relative humidity exceeds 70%.

The charged-media ionizing air cleaner combines the effects of the two types previously mentioned. The particles are charged in a corona-discharge type ionizer and then collected on a charged media filter mat. The ionizer increases the efficiency of the devices.

We can get an idea of a comparison of the removal efficiencies of these three devices from data presented by the NRC Committee on Indoor Pollutants in Table 1. It is seen that the most efficient of these devices is the two stage ionizing-type air cleaner. This is the type that will be examined in the rest of this presentation.

In the two-stage ionizing electronic air cleaner, a positive corona generates ions which attach to the dust particles. The reason for a positive corona, which is less efficient than a negatively generated corona, is that much less ozone is generated in the corona. In a typical design shown in Figure 5, a d.c. potential of 8-12 kV is used to create the ionizing field.

These charged particles then pass into the collector section where they are driven towards the collecting plate. Once the particles reach the collecting plate, they lose their charge and remain attached by molecular adhesion. The plates, being themselves charged, can sometimes impart this charge to the particle, and the particle can be driven off the collection plate. For the collection of dry dusts, it is sometimes advisable to coat the plates with an adhesive. In the collector section, the voltages are usually 4-6 kV.

The electronic air cleaner is an efficient low pressure drop device used with flow velocities of 100-500 ft/min. The efficiency of the device depends on the flow velocity through the device, the charging and collecting electric fields, the plate spacing and size, and the size distribution of the particulates being collected. This minimum produced in the efficiency curve is caused by the two charging mechanisms: diffusion and field charging. Diffusion charging occurs from the random motion of the ions causing them to impact on the particle. This charging mechanism is predominant for particles of diameters < 0.1 micron.

Field charging occurs when ions follow the electric flux lines which are deflected in the vicinity of the particle. Field charging becomes important for particles in the size ranges > 10 micron. In between 0.1 and 10 microns, both charging mechanisms become important.

This minimum on collection efficiency can also be shifted to larger particle sizes by decreasing the ionizer voltage or field strength. The minimum occurs at about 0.5-1.0 microns for ionizing fields reduced by a factor of 40. It is interesting to note that both media and electrostatic filters produce a minimum in the efficiency at about the same particle diameter, both from different physical collection mechanisms.

Since the efficiency is dependent on flow velocity, the electronic air cleaner often uses pre-filters to distribute the flow uniformly over the cross-sectional area. This pre-filter also removes lint and large particles which reduces the cleaning frequency. It also is a safety device to protect the ionizer section from damage. Post-filters are also sometimes used to collect any agglomerates which will eventually blow-off the plates.

The collection efficiency is a function of particle size and morphology. The current standard for measuring the efficiency of electronic air cleaners is the ASHRAE standard 52-76 and is known as the Atmospheric Dust Spot Test. Samples of the air upstream and downstream are passed through filter papers. The filters are then measured for optical transmissions to determine the efficiency of the filter in question. Another test for efficiency is the DOP testing used for high efficiency filters. The concentration of 0.3 micron DOP, generated at a concentration of 80 mg/m^3 , is measured upstream and downstream by a light scattering photometer.

APPLICATION OF EAC TO RADON DECAY PRODUCTS

Laboratory studies⁽¹⁶⁾ have determined that filtration methods are effective in the removal of a portion of the radon decay products. The removal efficiency of filter devices is dependent on attachment to dust, which decay product is being removed, and ventilation and infiltration rates.

To obtain more insight into the effectiveness of filtration on radon decay products in residences, a study was conducted to determine the removal efficiency using an electronic air cleaner. The measurements were made in a tight residence that had a forced-air furnace system with an electronic air cleaner in the return air duct and in an older residence that had hot-water heating. The electronic air cleaner used in the older residence was a stand-alone type.

The tight residence was a split-level home. Infiltration measurements made on this residence determined air exchange rates of 0.2 to 0.3 hr^{-1} during the time period

that the radon decay product measurements were made. The infiltration measurements were made using the tracer gas technique using methane as a tracer gas⁽¹⁷⁾.

Measurements were made in the basement of the residence using an EDA, Inc. WLM-300 working level monitor. With this instrument, working level readings were taken every hour. The data is stored in a microprocessor for later analysis. Along with this data, outdoor pressure and temperature readings were also made.

Background readings were first made with both the electronic air cleaner (EAC) and furnace fan off. The working levels obtained ranged between .001 and .035 WL. The fluctuations depend not only on the atmospheric pressure changes but also observed was a diurnal variation in the working level with a maxima during the early morning hours.

Once the background level had been established over a two week period, the EAC was then started. Figure 6 shows the resulting reduction in the working level. The WL was found to be reduced by 40-70%.

Testing was then done to try and determine the effect of the furnace fan on the reduction in WL. When the results with blower alone and then the blower-EAC combination were compared, it was found that on the average the blower produced a substantial reduction (70%), and the EAC-blower combination produced an 83% reduction in the WL. It was noted, though, that the fluctuations in the WL readings were reduced considerably by the blower-EAC combination. The blower produced a 40% reduction, while the blower + EAC produced a 76% reduction, as seen in Figure 7.

An older hydronic residence was measured using an EAC for WL reduction also. This residence was a two-story building heated using hot water. It had an infiltration rate of about 1.0 hr^{-1} . The EAC used in this test produced an effective air change of the same value as the furnace blower in the tight house. The testing for this residence was also done in the basement.

Working levels measured were about 5-8 WL with some excursions over 10 WL, as shown in Figure 8. No effect due to the EAC was seen and also no diurnal fluctuations were seen in the WL. This same residence was measured again during the summer and at this time, working levels in excess of 30 mWL were determined, and the diurnal fluctuations were seen also.

SUMMARY AND CONCLUSIONS

The electronic air cleaner is an efficient, low power device to collect particles over a wide range of particle sizes. It can operate in an air handling system producing a low pressure drop across the device.

There are several types of electronic air cleaners with the two-stage ionizing plate-type device being the most efficient. The efficiency of this device is dependent on the air flow through the electronic air cleaner as well as particle characteristics such as size, geometry, and dielectric constant. As with the media type filter, the electronic air cleaner has a minimum of about 0.3 microns due to the two particle charging mechanisms of diffusion and field changing.

In determining the effect of the EAC on radon decay products in residences, it was found that a reduction of up to 70% in the Working Level could be achieved with an electronic air cleaner mounted in the return air duct of a forced air furnace. The furnace fan/air moving system itself was found to reduce the Working Level, but by using a furnace fan-EAC combination, the large fluctuations of Working Level observed with both the background readings and the furnace blower-only readings could be reduced considerably.

The Electronic Air Cleaner is thus an alternative method to reduce particulate contaminant levels within residences and is effective in the reduction of the Working Level and its fluctuations.

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TABLE 1. Relative Performance of Electronic Air-Cleaners by Type^a.

TYPE OF CLEANER	REMOVAL EFFICIENCY, %		PRESSURE DROP, Pa	RELATIVE SPACE REQUIREMENT
	DUST SPOT METHOD	DOP METHOD		
Ionizing Plate	85-90	65-80	25-40	Maximal
Charged Media, Nonionizing	25-35	10-20	40-75	Minimal
Charged Media, Ionizing	40-60	25-35	40-75	Moderate

a. From Indoor Pollutants, Committee on Indoor Pollutants, NRC, 1981.

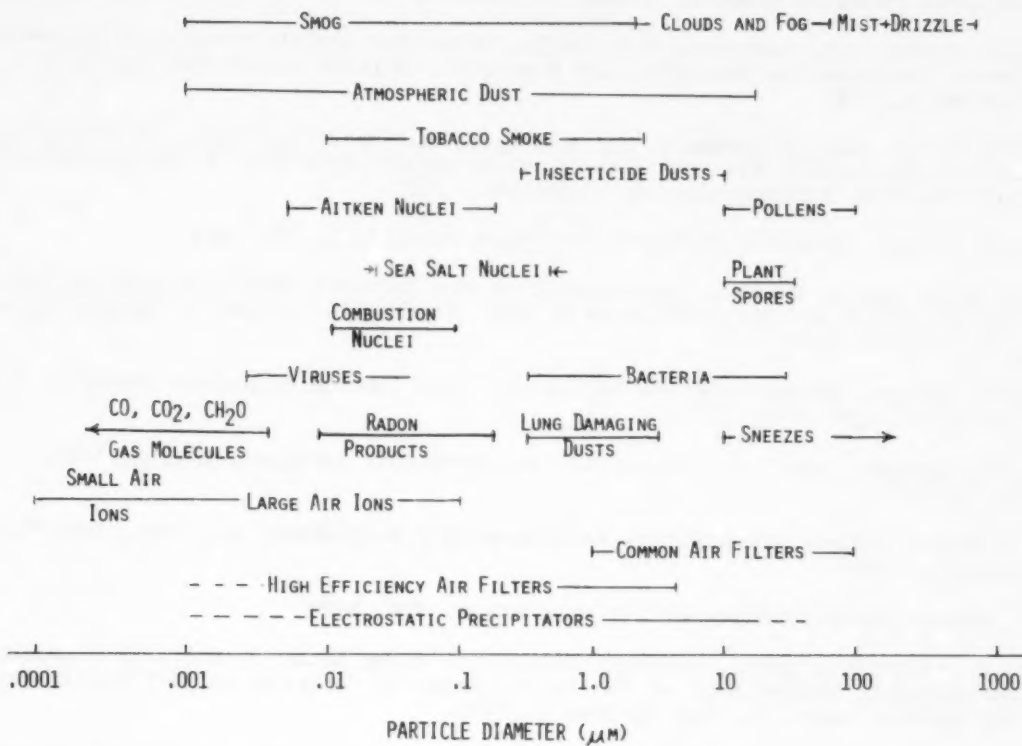


Figure 1. Size range of common indoor particles

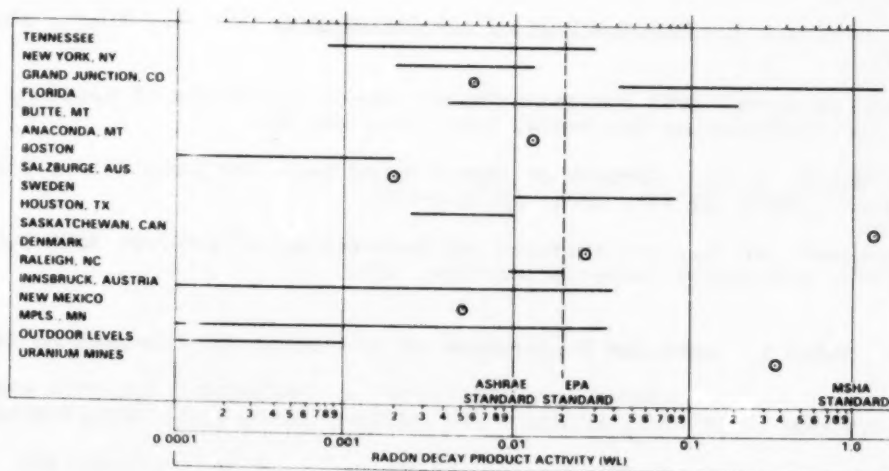


Figure 2. Indoor radon decay product activity levels

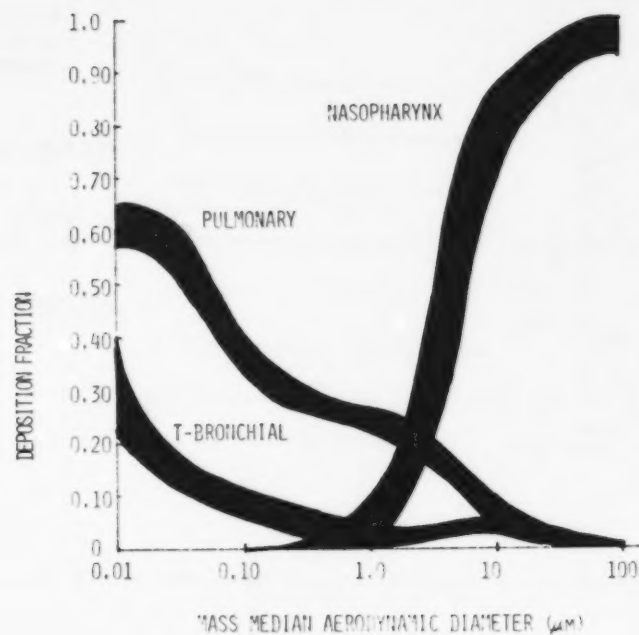


Figure 3. Deposition fraction in the lung

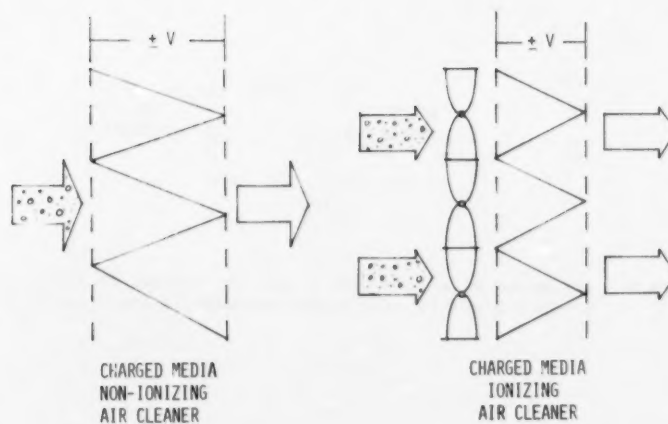
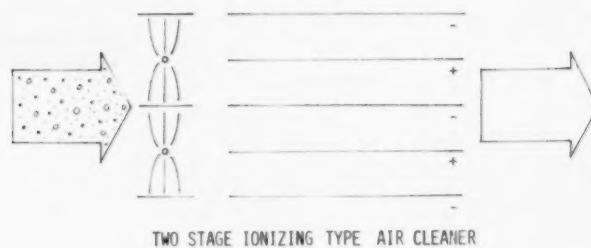


Figure 4. Three main types of electronic air cleaner

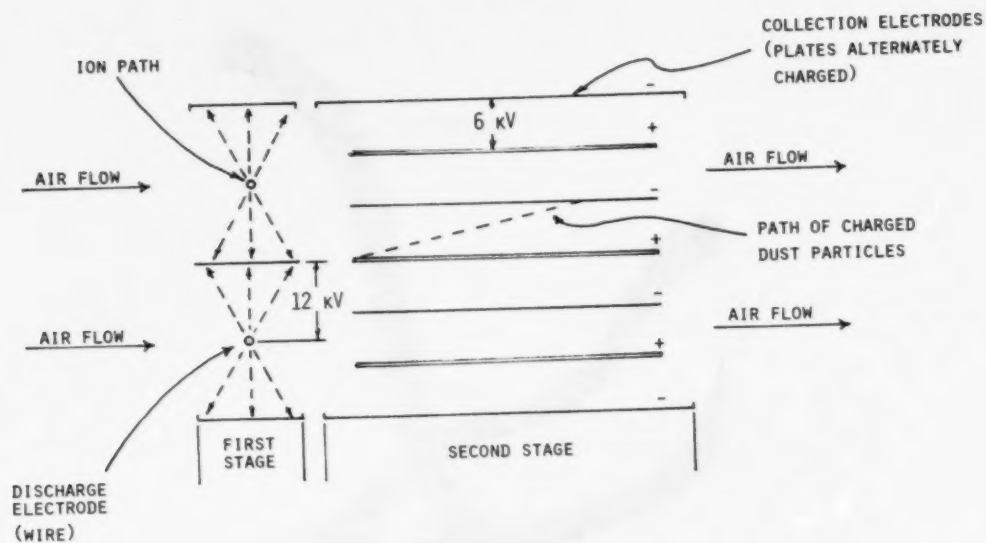


Figure 5. Schematic of a two-stage ionizing-type electronic air cleaner

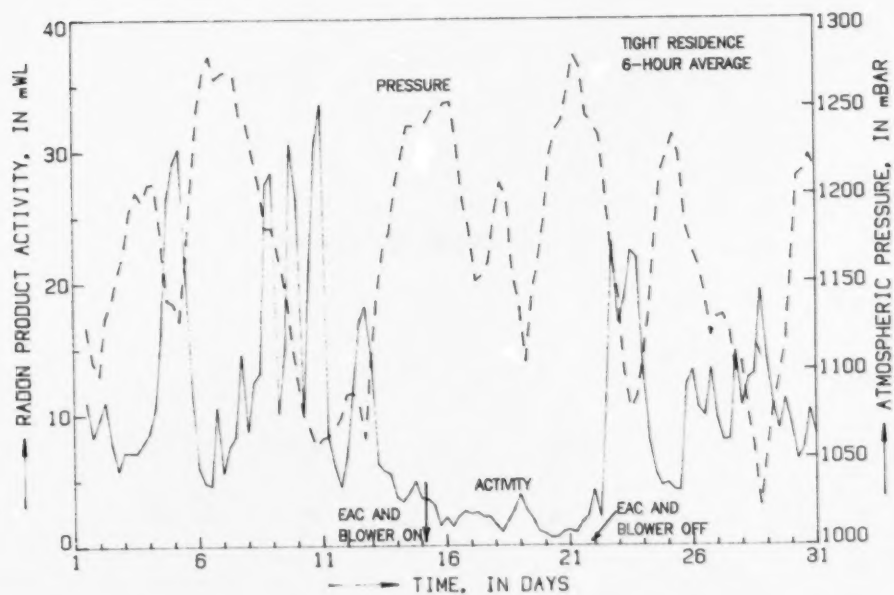


Figure 6. Influence of an electronic air cleaner on the radon decay product activity in a tight residential environment

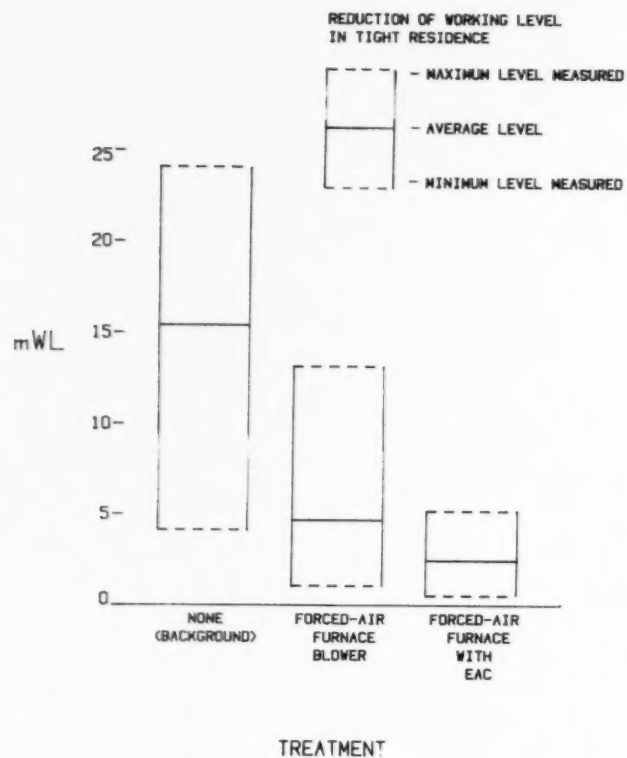


Figure 7. Reduction of working level fluctuations in a tight residence using an electronic air cleaner

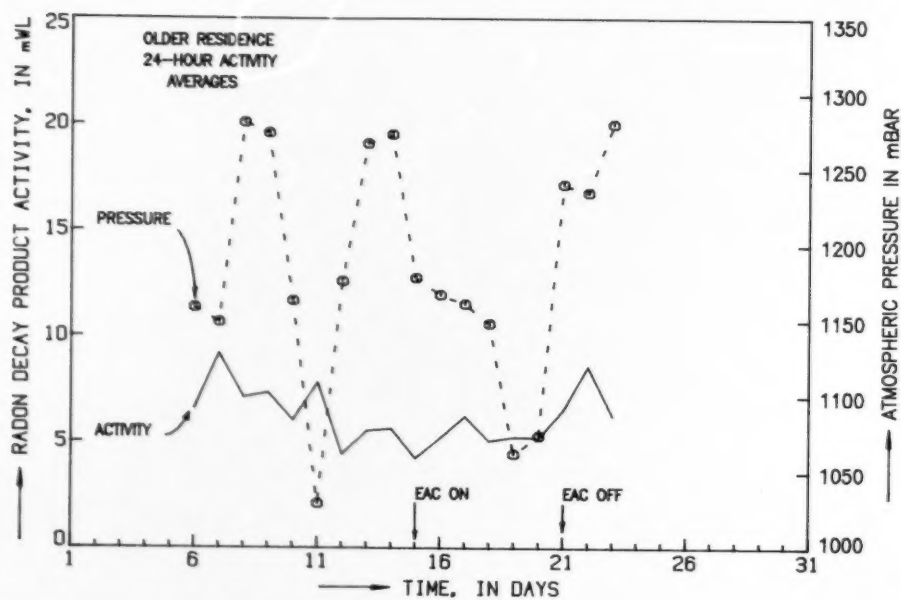


Figure 8. Influence of an electronic air cleaner on the radon decay product activity in an older residence

Air Cleaning with Granular Adsorbents

A. Turk, Ph.D.

The effectiveness of a granular adsorbent medium for air cleaning depends on two processes that occur in sequence. First, the molecules of a gaseous contaminant make contact with the solid surface of the medium and second, the contaminant must be retained and thus permanently removed from the air stream or it must be converted to an innocuous product.

The first process, making contact, distinguishes a granular medium from a filter. The kinetic motion of gas molecules is rapid enough (for example, about 400 m/s for nitrogen at 0 C) compared with the much slower kinetic motion of particulate matter so that it is possible to design granular beds that offer low resistance to air flow while offering effective contact with gas molecules. The adsorbents commonly used for indoor air cleaning are granules of mixed sizes ranging in diameter from about 0.04 to 0.2 in (1 to 5 mm) packed into beds of uniform thickness. Such arrangements offer relatively low resistance to airflow - about 6 in of water per ft (50 Pa per cm) of bed depth at a linear flow rate of about 50 ft/min (25 cm/s) (1). Under such conditions, the half-life of a molecule in the gas phase (before it reaches the surface of a granule) is about 0.01 s (2). Then, if an air stream containing contaminant molecules enters such a granular bed, the contact efficiency, E , which is the fraction of molecules that have contacted a solid surface after n seconds of residence time, is:

$$E = 1 - 2 (\exp -100 n)$$

From this equation, typical contact efficiencies are 75% for a residence time of 0.02 s, 93.75% for 0.04 s, and 98.44% for 0.06 s.

The second process, which is an action that prevents the return of the contaminant molecules to the air stream, may involve any of the following actions, or a combination of them: (a) physical adsorption, (b) chemical neutralization of an acid or a base, (c) oxidation, (d) addition or complexation, and (d) decomposition. The choice of a granular medium therefore involves a selection of the control process that is appropriate for the particular type of tightly enclosed space to be purified and for the contaminants expected therein. The spaces to be considered include residences, commercial buildings, and factories, in all of which the "tightness" of the enclosure is only moderate, as well as more tightly enclosed spaces such as storage areas and, tightest of all, submarines and space vehicles. Also to be considered are the requirements for duration of

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service and the options for regeneration or replacement. These modes of action of granular media, and the types of enclosed spaces and contaminants for which they are appropriate, are discussed in the following paragraphs.

(a) Physical adsorption Any gas or vapor will adhere to some degree to any solid surface. The factors that are important in practical air cleaning by physical adsorption are the molecular weight and electrical polarity of the gas or vapor and the polarity, surface characteristics, and total capacity of the adsorbent (3). The molecular weight of dry air (weighted average 29) is sufficiently lower than that of most air contaminants so that physical adsorption can effectively select for contaminants. Exceptions include ammonia (molecular weight 17), carbon monoxide (28), and the lighter hydrocarbons. Water vapor can be a problem because its high polarity gives it a strong affinity for polar adsorbents, which include all those containing oxygen, such as activated alumina, silica gel, and synthetic zeolites. As a result, water vapor renders such adsorbents ineffective for broad-spectrum removal of organic contaminants. Formaldehyde (molecular weight 30), however, can be selectively adsorbed by a synthetic zeolite of appropriate pore diameter, about 13 angstroms. It is because activated carbon lacks electrical polarity that it is the physical adsorbent of choice for practical use. Activated carbon thus rejects water and preferentially adsorbs organic vapors, while oxygenated adsorbents do the opposite. Other important factors in physical adsorption are the total pore volume and the distribution of pore diameters in the adsorbent. The total pore volume determines the capacity of the carbon to accommodate contaminants by capillary condensation, and the pore diameters influence the preference of the carbon for contaminants of different molecular size or shape. For example, a small-pore carbon, with a large fraction of its total pore volume in the "micropore" (diameters below about 30 Angstroms) range, is more effective for adsorption and retention of radon than is a carbon with a greater fraction of its pore volume in the "macropore" range (4). Finally, activated carbon that is impregnated with a reagent for removal of a specific class of contaminants may function simultaneously as a physical adsorbent if only a portion of its capacity is sequestered by the reactive impregnant. For example, a carbon impregnated with caustic for removal of hydrogen sulfide (see next paragraph) can also retain capacity for physical adsorption of other odorants.

(b) Chemical neutralization Activated carbon impregnated with caustic (NaOH or KOH) is effective for the neutralization of even very weak acids such as hydrogen sulfide or mercaptans. The capacity of the impregnated carbon (about 0.2 g hydrogen sulfide per g of carbon) is greater than can be accounted for by neutralization, and the difference is probably the result of oxidation of some of the sulfur to form polysulfides. Activated alumina can also be impregnated with a base, but not so strong a base as caustic, which reacts with alumina. Alumina impregnated with sodium carbonate will neutralize moderately strong acidic gases such as sulfur dioxide but will not, at the same time, retain a practically useful capacity for physical adsorption of a variety of air contaminants from a moist atmosphere. For removal of basic gases, activated carbon is impregnated with phosphoric acid, yielding a capacity for retention of about 0.1 g of ammonia per gram of impregnated carbon. Such impregnated carbon is also applicable for the removal of light amines.

(c) Oxidation Air contaminants may be oxidized to detoxify them, deodorize them, or render them more strongly retained on the granular adsorbent. The oxidizing agent may be a chemical impregnant on the adsorbent, or it may be air, in which case an oxidation catalyst on the surface of the adsorbent is generally necessary. An impregnated oxidant becomes exhausted as it is reduced by the air contaminants with which it reacts. An oxidation catalyst may become inactivated by being chemically poisoned or by being physically blinded by the accumulation of other adsorbed contaminants. When activated carbon is used as the substrate for an oxidation catalyst, its ignition temperature is somewhat reduced compared with that of the unimpregnated carbon. When the oxidation pathway is ionic,

the presence of some adsorbed moisture is necessary. These various factors dictate the choices for particular applications, such as the following: Activated alumina impregnated with potassium permanganate is used for removal of contaminants that are particularly labile to oxidation, such as formaldehyde. Permanganate oxidation of many other organics, however, is too slow to be completed in a single pass through a thin granular bed (5). On the other hand, the reduction product of the permanganate, which is manganese dioxide, can serve as a catalyst for the air oxidation of some of the components of stale tobacco odor. Oxidizing agents do not survive on activated carbon, because they are reduced by it. Carbon has been used for many years, however, as a support for oxidation catalysts. Platinized or palladized carbon is a powerful catalyst for air oxidation. Carbons impregnated with copper and/or silver catalysts were developed for the catalytic destruction of World War I type poison gases such as Lewisite and arsine. Even unimpregnated carbon is catalytically active, as evidenced by its promotion of the air oxidation of hydrogen sulfide to sulfur and polysulfides.

(d) Addition and complexation Some specific examples are of interest; the substrate in each case is activated carbon: Brominated carbon removes ethylene by converting it to the dibromide (6). Iodized carbon effectively removes mercury vapor; this action involves both oxidation and addition. Zinc acetate can remove ammonia and some amines by forming a zinc-ammonia or zinc-amine complex; this impregnation is advantageous over phosphoric acid when an acidic medium is to be avoided.

(e) Decomposition Activated alumina impregnated with a catalyst such as manganese dioxide or activated carbon with or without a metallic impregnation is an effective catalytic medium for the destructive decomposition of contaminants containing oxygen-to-oxygen bonds, such as ozonides, peroxides, hydroperoxides, and ozone itself.

(f) Combined actions Sequences of two or more granular beds may offer a combination of air cleaning processes.

Control Options for Particular Types of Enclosed Spaces

Residences and commercial buildings An unimpregnated activated carbon is best for removal of a broad spectrum of contaminants. If radon is a problem, a carbon with pore volume concentrated in the micropore range should be used. If formaldehyde is a problem, a combined system using activated carbon with either a synthetic zeolite or permanganated alumina can be effective.

Industrial spaces The medium of choice depends on the particular contaminant, such as iodinated carbon for removal of mercury vapor in lamp manufacturing, caustic-impregnated carbon for removal of sulfur gases in wastewater treatment plants, or phosphoric acid-impregnated carbon for ammonia removal in blueprint copying rooms.

Submarines Unimpregnated carbon is used for broad-spectrum air cleaning. Some cathodic gases, such as metal hydrides from battery operation, are readily oxidized.

Space vehicles For future applications involving long voyages it may be necessary to provide for reactivation in place. In such case, an activated carbon impregnated with an oxidation catalyst for reactivation by air oxidation may be appropriate (7, 8, 9).

Reactivation or Regeneration

Unfortunately, there is no convenient, generalized, automatic end-of-service-life indicator for activated carbon or other granular adsorbents in either HVAC or industrial systems. The gain of mass of the adsorbent depends, in part, on its retention of moisture, and is therefore

not a reliable index of saturation with non-aqueous matter. Resistance to airflow is not sensitive to degree of saturation. Carbon does not change color, and the surface change of purple permanganate to brown manganese dioxide may mask a residue of unreduced oxidant beneath. Even an instrumental monitoring of downstream total organic matter is unsatisfactory, because such detection is not correlated with odor or toxicity. The two practical, if not most convenient, approaches are: (a) a representative sample of the adsorbent is removed from the system and analyzed for its degree of saturation or assayed for its performance under standard test conditions, and (b) the downstream air is analyzed for the specific contaminants to be removed or is evaluated for its odor by human judges.

Media containing exhausted oxidants such as manganese compounds are discarded. Activated carbon saturated with organic matter can be reactivated, but such processing requires superheated steam, and is therefore not practicable in HVAC systems. If sufficient quantities can be accumulated, the saturated carbon can be returned to the manufacturer or elsewhere for bulk reactivation. In some particular cases involving a specific impregnant or contaminant an ambient temperature regeneration may be feasible. For example, carbon impregnated with caustic for removal of hydrogen sulfide may be regenerated by washing out the sulfide or sulfate salts with water and reimpregnating the carbon with caustic. As another example, carbon saturated with ethylene dibromide (EDB, an agricultural fumigant) can be regenerated by washing with a caustic solution that converts the EDB to water-soluble ethylene glycol. In the special case of activated carbon that may be used as an air cleaner in prolonged space voyages, preliminary studies indicate that platinized or palladized carbon may be catalytically reactivated in place by selective oxidation of the adsorbate without oxidizing the carbon (10).

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Air Mixing Efficiency

J.E. Janssen, P.E.

INTRODUCTION

ASHRAE Standard 62-1981, "Ventilation for Acceptable Indoor Air Quality"⁽¹⁾ and its predecessor 62-73⁽²⁾, "Natural and Mechanical Ventilation", specify the amount of outdoor air to be supplied to an indoor space depending on the occupancy level, activities, and other factors. Both standards assume that all of the air supplied to a space is available for diluting the contaminants. Tracer gas studies made in the past few years have shown that this is a poor assumption^(3,4). Incomplete mixing of the outdoor dilution air with contaminated room air is frequently the result of the location of the ventilation supply outlet and return inlets in a room. Bypassing of supply air to the return system with subsequent exhaust of a part of the return air reduces the amount of outdoor air available for dilution of room air contaminants. Thus, the amount of outdoor air effectively used is often substantially less than the amount recommended by the Ventilation Standard. Further, there are no satisfactory means available today for building owners, contractors, or inspectors to measure the actual ventilation effectiveness.

The level of contaminants in any space is the result of the balance between the contaminant generation rate and the dilution and removal rates. The horror stories associated with the "sick building syndrome" may be the result of excess contaminate generation or of inadequate dilution and removal. The question of ventilation effectiveness is further compounded by the fact that the air circulated to a space usually is also the heat transfer medium for heating or cooling the space. This does not present a serious problem with constant volume systems, but it does present the designer with serious challenges in the design of energy efficiency variable air volume systems. Air circulation rates can be at a minimum when occupant density is maximum.

Research the past few years is providing insight into these problems. Mathematical models and experimental measurements provide an understanding of the problem and give clues for its solution.

VENTILATION MODELS

Ventilation effectiveness or efficiency can be considered from two points of view. A model can be developed to account for the outdoor air that is inducted and subsequently exhausted without being used. The more conventional approach is to calculate contaminant concentrations on the basis of the contaminant generation rate and the amount of dilution air delivered to the occupied space or a point in the space.

The duct arrangement shown in Figure 1 is typical of most heating ventilating and air conditioning systems that use air as the heat transfer medium.

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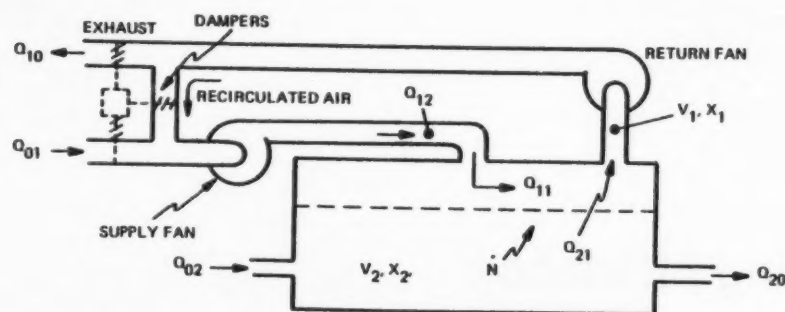


Figure 1.

A supply fan supplies mixed air (a combination of outdoor air and recirculated air) to the occupied space, frequently through ceiling diffusers. This air is returned (sometimes with the aid of a return air fan) to a duct intersection that is controlled by two dampers that operate 90° out of phase. Some of this return air is exhausted and some is recirculated. The ratio is determined by the position of the exhaust and recirculation dampers. A third damper in the outdoor air duct operates in phase with the exhaust damper. The room or occupied space usually has leakage openings that permit infiltration of outdoor air with subsequent exfiltration of indoor air as represented by the flow Q_{02} and Q_{20} .

The ceiling diffusers employ relatively high velocity jets to distribute the supply air to the occupied level in the space. Diffusers are designed to achieve acceptable draft temperature. Sedimentary comfort conditions have been found to exist when the effective draft temperature is between -1.7 and $+1.1^{\circ}\text{C}$ (-3 to $+2^{\circ}\text{F}$) (5). This will be shown later to be a combination of temperature and air velocity. Much attention has been focussed on the location and performance of the supply diffusers from the thermal point of view. Diffusers have been rated in terms of an "Air Diffuser Performance Index" (ADPI). This defines a diffuser's ability to distribute air without producing uncomfortable drafts in occupied areas of a space. Return air inlets have little effect on thermal comfort conditions in a room, and thus, have received little attention. Location of the return air inlet has a more profound influence on ventilation effectiveness, however.

Consider Figure 1. If the supply outlet and return inlet are both located in or near the ceiling, it is possible for part of the supply air to bypass the occupied level of the space. This bypass flow is represented by Q_{11} in Figure 1. This can be called a stratified or bypass flow and can be represented by:

$$Q_{11} = s Q_{12}$$

where,

- Q_{11} is the stratified flow in a room;
- Q_{12} is the total supply flow to a room;
- s is a stratification factor.

The flow returned from the space is Q_{21} , and the total return flow is $Q_{21} + s Q_{12}$. A fraction, r , of this return flow is recirculated and the remainder, $1-r$, is exhausted. We can now write a material balance for a quantity of outdoor air, Q_{01} , that enters the system. We will assume there is no infiltration, i.e. $Q_{02} = Q_{20} = 0$. The amount of this outdoor air that bypasses the occupied space and is exhausted is:

$$Q_{10-s} = (1-r) \cdot (Q_{01}) (s) + (1-r) (rs) (Q_{01}s) + (1-r) (rs)^2 (Q_{01}s) + \dots \quad (1)$$

$$= s (1-r) (Q_{01}) [1 + rs + (rs)^2 + \dots] \quad (2)$$

$$\frac{Q_{10-s}}{Q_{01}} = \frac{s (1-r)}{(1-rs)} \quad (3)$$

We can define a ventilation efficiency as:

$$\eta_v = \frac{Q_{01} - Q_{10-s}}{Q_{01}} = 1 - \frac{s(1-r)}{1-rs} = \frac{1-s}{1-rs} \quad (4)$$

Equation (4) defines the efficiency with which the outdoor air is circulated to the occupied space in terms of a stratification or mixing factor, s , and the recirculation factor, r . If there is no exhaust flow, $r = 1$ and the efficiency is 100%. If there is no stratified or bypass flow, $s = 0$, the efficiency is also 100%. If however, there is both stratified flow and recirculation, outdoor air can pass through the system without ever being used to dilute contaminants at the occupied level. This ventilation loss also represents an energy loss.

The outdoor air that is inducted must be heated or cooled to supply-air enthalpy conditions but will be exhausted at return-air enthalpy conditions. This, in theory, can be measured by measuring the difference between the room-air enthalpy at the occupied level and the return or exhaust-air enthalpy under heating conditions, the return-air enthalpy should be slightly higher than that quality at the moment, however. Tracer gas measurements can provide a more sensitive measurement of this stratified or bypass flow.

Ethridge⁽⁶⁾, Sandberg⁽⁷⁾, and Skarret⁽⁸⁾ have used a two chamber model to develop ventilation efficiency equations. The ductwork and upper or unoccupied part of a room can be considered as one chamber with a volume, V_1 , and the lower, or occupied part of the room can be considered the second chamber with a volume, V_2 . These are shown in Figure 1. The dotted line represents the effective boundary between the two chambers.

Assume that a tracer gas is injected into the supply duct (Chamber 1) at a rate, $\dot{N}$. The concentration of the tracer gas is X_1 in Chamber 1 and X_2 in Chamber 2. The rate of change of concentration of the tracer gas in the two chambers is:

$$V_1 \frac{dX_1}{dt} = \dot{N} - (Q_{10} + Q_{12}) X_1 + Q_{21} X_2 \quad (5)$$

and,

$$V_2 \frac{dX_2}{dt} = Q_{12} X_1 - (Q_{21} + Q_{20}) X_2 \quad (6)$$

These equations can be integrated and solved for the tracer gas concentrations X_1 and X_2 .

$$X_1 = \frac{h\dot{N}'}{bh - ag} + C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t} \quad (7)$$

$$X_2 = \frac{g\dot{N}'}{bh - ag} + \frac{C_1}{a} (\lambda_1 + b) e^{\lambda_1 t} + \frac{C_2}{a} (\lambda_2 + b) e^{\lambda_2 t} \quad (8)$$

where,

$$a = Q_{21}/V_1 \quad (9)$$

$$b = (Q_{10} + Q_{12})/V_1 \quad (10)$$

$$g = Q_{12}/V_2 \quad (11)$$

$$h = (Q_{21} + Q_{20})/V_2 \quad (12)$$

$$\dot{N}' = \dot{N}/V_1 \quad (13)$$

$$\lambda_1 = 1/2 [-(b+h) + \sqrt{(b+h)^2 - 4(bh - ag)}] \quad (14)$$

$$\lambda_2 = 1/2 [-(b+h) - \sqrt{(b+h)^2 - 4(bh - ag)}] \quad (15)$$

Figure 2 and 3 present theoretical tracer gas concentrations in a space for an assumed set of conditions. Figure 2 is the calculated tracer gas concentration. The tracer gas generation rate was chosen to produce a concentration of 500 ppm at the end of one hour if there were no losses from the system. The other parameters are given on the figure. Figure 3 is a plot of the natural logarithm of the tracer gas concentration in each chamber during the decay

period (i.e., $\dot{N}' = 0$). If mixing were complete at the beginning of the decay period and the interchamber flow rates maintained perfect mixing, the concentrations would be the same in both chambers and the decay would be a single straight line on the semi-log plot. Any departure from a single straight line on a semi-log plot indicates incomplete mixing.

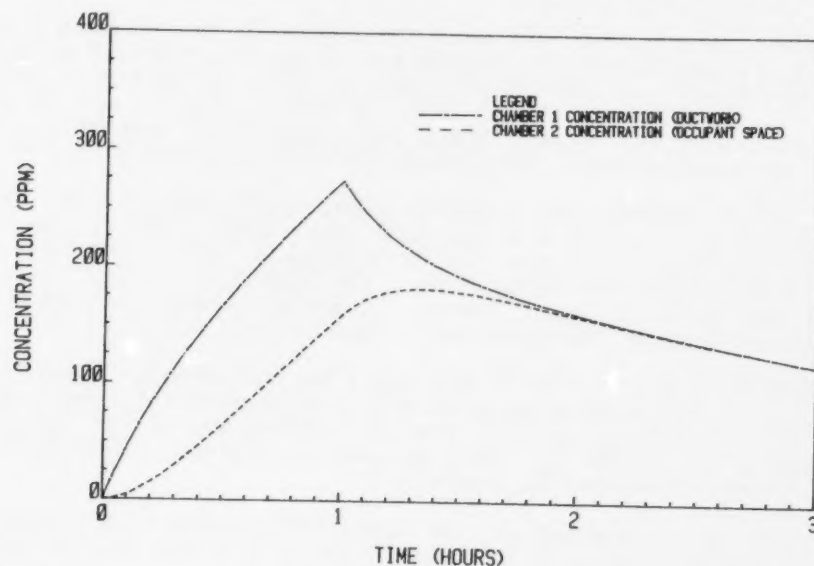


Figure 2. Tracer concentration buildup-decay

Two chamber model: Interchamber flowrates (Q'_{12} , Q'_{21} , Q''_{21}) = 2.0 ACH
Ventilation rates (Q'_{10} , Q''_{20}) = 0.3 ACH

A ventilation efficiency function can be defined from the various flow rates. Referring to Figure 1, the maximum reduction rate of X_2 would occur when $Q_{10} + Q_{20}$ removes tracer gas at a concentration X_2 . The actual removal rate is $(Q_{21} + Q_{20})X_2 - Q_{12}X_1$. Thus, the efficiency with which gas is removed is given by:

$$\eta_v = \frac{(Q_{21} + Q_{20}) X_2 - Q_{12} X_1}{(Q_{10} + Q_{20}) X_2} \quad (16)$$

$$= \frac{Q_{21} + Q_{20} - (X_1/X_2) Q_{12}}{Q_{10} + Q_{20}} \quad (17)$$

The slopes of the curves in Figure 3 are related to the flows in volume changes per hour. Thus, we can write the flow terms in equation (17) in terms of the volumetric change rates using equation (9-12). Note that:

$$Q_{21} + Q_{20} = hV_2 \quad (18)$$

$$Q_{12} = gV_2 \quad (19)$$

$$Q_{10} = bV_1 - gV_2 \quad (20)$$

$$Q_{20} = hV_2 - aV_1 \quad (21)$$

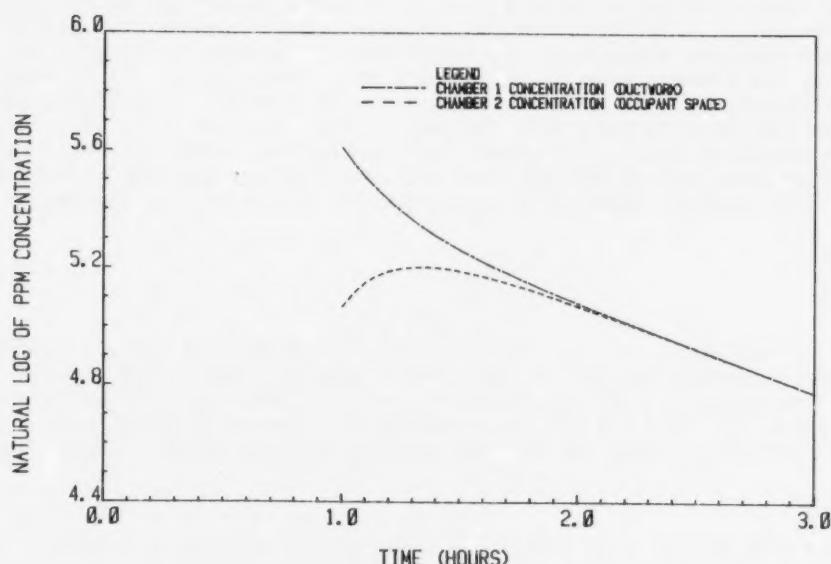


Figure 3. Tracer concentration decay

Two chamber model: Interchamber flowrates (Q'_{12} , Q'_{21} , Q''_{21}) = 2.0 ACH
Ventilation rates (Q'_{10} , Q''_{20}) = 0.3 ACH

$$\eta_v = \frac{hV_2 - gV_2 (X_1/X_2)}{(bV_1 - gV_2 + hV_2 - aV_1)} = \frac{h - g (X_1/X_2)}{(h - g) + (b - a) (V_1/V_2)} \quad (22)$$

In theory, it should be possible to work backward from measured concentrations in each chamber to compute the ventilation efficiency using equation (22). For the decay period, i.e., $\dot{N} = 0$, equation (5) and (6) can be simplified with the aid of equation (9), (10), (11), and (12).

Then,

$$dX_1/dt = -bX_1 + aX_2 \quad (23)$$

$$dX_2/dt = gX_1 - hX_2 \quad (24)$$

Values can be read from the curves at two different times to evaluate equation (23) and (24). The values for a , b , g , and h then can be used to evaluate the efficiency as defined by equation (22). The concentration ratio, X_1/X_2 , would be the steady state tracer gas concentration in the two chambers. This would be approximated at a decay time long enough for the concentration in the two chambers to be decaying at nearly the same rate.

The test should be made with the tracer gas introduced into the occupied chamber, i.e., to simulate a contaminant generated by the occupants. Failure to introduce the tracer gas into the same chamber in which the contaminants of importance are generated will require a careful examination of the model to account for changes in signs.

Equation 22 still has one unknown, the volume ratio, V_1/V_2 . If the supply volume flow is equal to the return volume flow, i.e.:

$$Q_{12} = Q_{21} \quad (25)$$

then,

$$V_1/V_2 = g/a \quad (26)$$

This is generally the case when the exhaust is taken from the return air flow. It will not be true, however, if the exhaust system is separate from the return/recirculation system.

Determination of the effective volumes, V_1 and V_2 , from the tracer gas decay tests will be influenced by the points at which tracer gas concentrations are measured. Measurements for V_1 should be made near the entrance to the return duct. The concentration in the return duct was assumed to be the concentration in the exhaust air. Measurements for V_2 should be made at a point of interest, e.g. an occupied location in the room or a source of a contaminant. The computed ventilation efficiency will then be for that location. The bypass factor, S , will define the deviation from a well mixed condition for the outdoor air reaching that point. The ventilation measured by a tracer gas test and computed from e.g. (22) can be equated to equation (5). This equation then can be solved for the stratification factor, S .

$$S = \frac{1 - \eta_v}{1 - r\eta_v} \quad (27)$$

If there is no recirculation, $r = 0$, stratification is a measure of the efficiency loss. If there is complete recirculation, $r = 1$, there is no exhaust from the air handler, $Q_{10} = 0$, and it appears from equation (28) that stratification is 100%. Under these conditions, however, any outdoor air inducted must be exhausted through the occupied space and appear as flow Q_{20} . Thus, efficiency would be 100% and equation (27) would be indeterminate.

PERFORMANCE INDEX

The Air Diffuser Performance Index (ADPI) was developed to describe the comfort (i.e., the heat transfer) characteristics of a diffuser on occupants. It depends on the air velocity, temperature and direction as the air leaves the diffuser. It has been found that sedentary people are comfortable if the "effective draft temperature" is between -1.7 and $+1.1^\circ\text{C}$ (-3 and $+2^\circ\text{F}$) and the air velocity is less than 0.35 m/s (70 fpm).⁽⁵⁾ The effective draft temperature is defined as:

$$Q = (t_x - t_c) - a(u_x - b) \quad (28)$$

- t_x = local temperature, celsius (Fahrenheit)
- t_c = average room temperature, celsius (Fahrenheit)
- u_x = local air velocity, m/s (fpm)
- $a = 8$ (0.07)
- $b = 0.15$ (30)

The ADPI is defined as the percentage of locations which fall within the acceptable effective draft temperature range. The location of the return air inlet has little effect on the ADPI except close to the inlet where air velocities increase.

The design of the return air system will, however, have a large effect on a ventilation performance index. The exhaust system will be most effective if the air is taken from a region close to the source of the contaminants where the concentration is highest, consider Figure 1. If the contaminants are being generated by the occupants (e.g., CO_2), the exhaust should all be represented by Q_{20} . The flow, Q_{10} , should be zero. Then the outdoor air trapped in the stratified flow, Q_{11} , will be recirculated until it is mixed. Under these conditions the efficiency equation, e.g. (17) becomes,

$$\eta_v = \frac{Q_{21} + Q_{20} - (X_1/X_2) Q_{12}}{Q_{20}} \quad (29)$$

The return flow, Q_{21} , will be smaller than the supply flow by the amount of the outdoor air flow, Q_{01} .

$$Q_{12} = Q_{21} + Q_{01} \quad (30)$$

Assuming there is no contaminant in the outdoor air, the material balance for the contaminant becomes:

$$Q_{12}X_1 = Q_{21}X_2$$

$$Q_{21} = (X_1/X_2) Q_{12}$$

(31)

Introducing equation (22) in (19) shows that ventilation efficiency will be 100% under these conditions.

It is clear then that a ventilation performance index and ventilation efficiency are strongly influenced by the location and design of both the supply and return air systems. A flow pattern which approximates plug flow through the occupied space achieves the highest efficiency.

CONCLUSIONS

The wide-spread use of air distribution systems in buildings to both transfer heat and ventilate the space has lead to practices which compromise the efficiency of both systems. The common practice of locating both the supply air diffusers and return air inlets in or near the ceiling permits bypassing of a significant amount of supply air directly to the return air system. This wastes energy in conditioning air that is not effectively used and it leads to indoor air contaminant levels that are higher than they would be if all of the outdoor air were effectively used. The problem is likely to be most serious with variable air volume systems where increased occupant load can lead to a lower thermal load in winter with reduced ventilation at a time when contaminant generation (CO_2 , tobacco smoke, etc.) is increased.

Tracer gas decay measurements and a two-chamber model provide a means of measuring the fraction of the flow that passes from the supply outlet directly to the return inlet, bypassing the occupied part of a room. This analysis also shows the desirability of separating the return/recirculation system from the exhaust air system. Energy can be saved and air quality can be improved when this is done.

Research is needed to define the magnitude of the loss in ventilation efficiency caused by poorly designed return air systems. The effect of incomplete air mixing in rooms needs to be addressed in the ASHRAE Ventilation Standard.

ACKNOWLEDGEMENT

The author would like to express his thanks to David T. Grimsrud of Lawrence Berkeley Laboratory, for suggesting and providing an example of the two chamber model. He would also like to recognize the services of J. Ward MacArthur and Thomas Hill of Honeywell Technology Strategy Center in solving and programming the differential equations.

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Air Infiltration and Indoor Air Quality— A Critical Review

R.A. Macriss

ABSTRACT

In one- to six-unit residential dwellings, natural ventilation and uncontrolled air infiltration are expected to be the predominant mechanisms for comfort and indoor air quality control in the foreseeable future. Air infiltration is also expected to be responsible for a progressively larger share of the total heat losses in future new residential construction.

Simple design-day or time-averaged air infiltration knowledge is quite sufficient for energy conservation considerations and various tracer gas or passive techniques can be used to acquire it. On the contrary, such techniques can be cumbersome, time consuming and prohibitively expensive, when used alone to characterize the influence of air infiltration on comfort and, especially, on indoor air quality.

Various models have been developed to facilitate the estimation of detailed and internally consistent air infiltration data. These models have, generally, been based on first principles and on actual data developed under laboratory or field conditions. The actual data used for model development and verification have either been obtained by the fan-pressurization method or by tracer gas techniques. The predictive ability of the existing models has also been tested by third-party investigators in this country and abroad.

This presentation is intended to cover comprehensively the factors affecting air infiltration and indoor air quality, the utility of existing air infiltration models, and the ideal and practical requirements of a relevant indoor air quality model that could be used as a tool for management of atmosphere in tightly enclosed residential spaces.

INTRODUCTION

The single most effective way to conserve energy in residential buildings is to reduce heating and air conditioning demands. This is most easily accomplished by reducing air infiltration (natural ventilation) of buildings, especially during periods when heating or air conditioning equipment is being operated. A growing trend in new construction substantially reduces infiltration, with such reductions often made from typical levels of about 1.0 air change per hour (acph) to as little as 0.2 acph.

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Most recently, concern has been focused on the impact of "energy conservation-through-infiltration reduction" (in new building construction) on indoor air quality (IAQ), and particularly on the role of NO_x (NO and NO_2) and CO (from unvented fossil-fueled appliances), formaldehyde (from wall insulation), freons (from aerosol sprays), and radon (from concrete, stone, ground water). As a result, the attention of researchers and governmental bodies began to shift to aspects of indoor air quality, and its relationship to indoor air pollution epidemiology, to potential emission control strategies for indoor contaminants, and to the control of indoor humidity.

Most of these efforts have focused exclusively on simple air dilution for indoor contaminant and moisture control, in tight residential atmospheres, by employing forced ventilation (with heat recovery) schemes, and equipment usually known as Air-To-Air Heat Exchangers (ATAHE). Already, serious drawbacks (payback, ventilation efficiency, etc.) and other potential shortcomings (core freeze-up, heat exchanger surface fouling, etc.) have been identified, regarding presently available equipment.

In addition to "source" emission control of unvented appliances (low NO_x burners), "source" exclusion for formaldehyde and asbestos (surface masking or covering with sealants) and ATHAE equipment, there are at least two other strategies for reducing contaminant concentration levels within residences, which may be proven potentially most cost effective. These are combinations of "direct" exhaust spot ventilators with air cleaning (active agent) filters or cartridges, located near the source and activated by it, and "integrated" controls which can respond to the dwelling atmosphere needs, as opposed to a specific emission source or air contaminant.

Proper implementation of the former, and particularly of the last two approaches, require comprehensive understanding of the factors affecting air infiltration and indoor air quality, of the utility of available means to characterize both, and of the practical requirements of an indoor air quality model, to be used as a tool for the management of atmosphere in tightly enclosed residential spaces.

This paper presents a summary critical review of the state-of-knowledge of air infiltration measurement and modeling for indoor environment control, with particular emphasis on emissions, contaminants, and sources related to fossil-fueled residential equipment.

DISCUSSION

My purpose of performing a summary Critical Review of the relationship between residential air infiltration and indoor air quality stems from the need, I perceive, for a consensus approach to be used in the assessment and control of the quality of the indoor environment. Very significant and extended efforts have been undertaken, during the last decade, in the understanding, measurement and modeling of air infiltration for energy conservation purposes. On the other hand, only recently has there been an interest in the comprehensive characterization of indoor air quality, and its ultimate control, under "real world" conditions. Earlier efforts have been limited to laboratory simulation studies, "controlled home" case studies of limited applicability, and field epidemiologic surveys in which indoor environment characterization was only crude, insufficient or irrelevant to the understanding of the factors affecting it.

One part of the problem arises from general lack of comprehensive understanding, in my view, of the role played by air infiltration; another part, from the attempt to gain such understanding, on a case-by-case basis, through limited (due to cost) air infiltration measurements. Even worse, such limited understanding is at the base of currently available IAQ control approaches and equipment of limited or questionable value to the consumer, and of air infiltration control techniques which, by aggravating the IAQ problem, tend to necessitate remedial actions that can be conveniently provided by less than adequate equipment and methods.

My attempt to provide the need for a dialog, among those active in a field which is at once very complex and challenging, has necessitated that I focus on "Critical" rather than on "Review". There is recent precedent for this approach, and I do not claim novelty, but I have also endeavored to provide sufficient reference material for the major subjects covered, for anyone to pursue a "review" option of these subjects on his/her own.

1. Residential Air Infiltration

Historical trends in new residential dwelling construction have resulted in gradual decreases in air leakage rates (or air infiltration) of the building envelop. For the foreseeable future, this trend is expected to continue so that air infiltration (natural ventilation) rather

than forced ventilation will be the predominant mechanism for IAQ control due to the low turnover rate of the building stock.¹

Enhanced public awareness of the need for energy conservation has also resulted in similar decreases in existing dwellings and this trend should continue in the future as a result of —

- Gradual replacement of chimney-vented appliances (e.g. gas furnaces) with through-the-wall-vented higher efficiency models.²
- Projected proliferation of unvented space heaters,³ either as the only source or for supplemental space heating, due to the gradual reduction of the building's heat loss rate.

Relatively tight homes are not a novelty of the last decade but have been around through the 1950's and 60's. With the exclusion of inner-city dwellings and rowhouse structures, city perimeter and suburban single family dwellings in the East and West North Central states, that have been equipped with central forced air heating and air conditioning, are examples of such homes. In these homes, weatherstripping, caulking and year-round use of storm windows and doors have been standard practice, with the number of such homes increased as central air conditioning saturation increased in homes built after World War II.

Table 1 summarizes the characteristics of 23 test homes in the Chicago Metropolitan area, tested by IGT in 1976-77, varying in age from 2 to 130 years. Table 2 is a summary of weather and other data, and corresponding air infiltration data while the furnace is operating, for 12 of these test homes. Table 2 shows that the measured air infiltration rates varied between 0.16 and 0.67 air changes per hour (acph), inspite of the large variability in characteristics and weather between homes.⁴ These measurements were carried out using a tracer technique, with ethane (C₂H₆) gas used as the tracer.

Table 1
23 FIELD TEST HOMES
—CHARACTERISTICS—

AGE:	2-130 yr
SIZE:	800-3850 ft ²
CONSTRUCTION:	BRICK, FRAME, COMBINATIONS
HOUSE HEIGHT:	1-, 2-STORY, SPLIT LEVEL
FURNACE INPUT:	50,000-160,000 Btu/h
CHIMNEY HEIGHT:	12-34 ft
VENT DIAMETER:	4-6 in.

Table 2.
AIR INFILTRATION DATA
FROM CHICAGO FIELD HOMES

OCCUPANT NAME	FURNACE INPUT, CFM	INDOOR TEMP., °F	OUTDOOR TEMP., °F	WINDSPEED & DIRECTION, MPH	AIR INFILTRATION		
					CHIMNEY CLOSED SCFM	BURNER ON	ON ACPH
INGEMANSON	93	69	60	S 14	98	111	0.36
SCHALK	126	69	61	S 18	143	145	0.67
VAVRIK	122	68	58	W 8	79	97	0.32
MURA	122	69	67	S 15	84	107	0.55
PATTERSON	110	72	59	SW 23	96	119	0.41
WHITE	117	74	50	S 10	170	211	0.46
WEBER	90	71	40	SW 21	59	51	0.16
SODERQUIST	128	76	67	S 14	95	179	0.60
SIMPSON	108	72	62	S 7	128	136	0.43
STAATS	115	72	61	S 16	187	199	0.50
MACRISS	72	65	35	SW 19	78	107	0.45
HIRSH	107	72	35	SW 16	53	91	0.38

In the ensuing years, air infiltration measurement techniques and instrumentation have improved substantially in the U.S. and abroad, and a recent publication⁵ presents a comprehensive review of most alternative tracer gas techniques, pressurization methods, and other miscellaneous approaches, and of instrumentation. These improved methodologies and instrumentation, coupled with weather measuring equipment, have broadened the scope, detail and accuracy of air infiltration and air leakage measurements possible. On the other hand, use of these techniques for extensive and comprehensive measurements can be time consuming and, therefore, prohibitively expensive. In order to reduce cost or increase cost effectiveness, additional passive techniques⁶ have been recently proposed.

Due to high measurement costs, the tendency has been to limit air infiltration characterization to the "whole house". As shown in Table 3, knowledge of whole house air infiltration is useful for energy consumption and conservation considerations.⁷ On the other hand, comfort and indoor air quality are affected or controlled by local sources (window leakage of cold air-draft, emission source - kitchen range) and, therefore, whole house air infiltration is of little value in these cases.

Table 3.
HEATING SEASON AVERAGE INFILTRATION
AND INDUCED HEATING LOAD

HOUSE	WASHINGTON, D.C.			MADISON, WISCONSIN		
	HEATING SEASON AVG. INFIL'TN RATE		AIR INFIL'TN HEATING LOAD, therms	HEATING SEASON AVG. INFIL'TN RATE		AIR INFIL'TN HEATING LOAD, therms
	cfm	ACPH		cfm	ACPH	
IGT-CC	165	0.72	267	187	0.81	445
IGT-CW	124	0.56	201	140	0.63	334
OSU-KTSC	113	0.39	180	131	0.45	304
OSU-SRSG	134	0.34	212	151	0.38	351
TAMURA	39	0.21	62	44	0.23	102

Washington: Heating Season, 4774 h, 40.7 °F, 8.4 mph
Madison: Heating Season, 5487 h, 33.0 °F, 10.1 mph

Isolated measurements of air infiltration, or single number characterization of the air exchange rate of a single family dwelling, are of very limited value to energy conservation, comfort or indoor equality. Table 4 illustrates the effect of a chimney and furnace operation on the seasonal range, seasonal mean, minimum and maximum air infiltration rates, measured in the 23 IGT test homes mentioned earlier.⁴ Table 5 summarizes monthly average and monthly and yearly maximum and minimum air infiltration rates, in another IGT test home.⁷ Finally, Table 6 illustrates the effect of weather and of a solarium, in a passive solar home, on measured air infiltration rates.⁷

Table 4.
23 FIELD TEST HOMES
-AIR INFILTRATION RATES-

	ACPH
WITH FURNACE ON	
SEASONAL RANGE	0.30-1.7
SEASONAL MEAN	0.67
MINIMUM	0.25
MAXIMUM	2.65
WITH CHIMNEY CLOSED	
SEASONAL RANGE	0.25-1.25
SEASONAL MEAN	0.55
MINIMUM	0.12
MAXIMUM	2.41

Table 5.

MONTHLY AVERAGE, MAXIMUM AND
MINIMUM, AIR INFILTRATION RATES
IGT-CW HOME/MADISON

MONTH	HOURS	AVG. T, °F	AVG. WS, mph	AVG. ACPH	MAX. ACPH	MIN. ACPH
JANUARY	744	17.0	10.1	0.54	0.79	0.36
FEBRUARY	672	21.3	11.3	0.54	0.87	0.43
MARCH	744	28.7	12.4	0.52	0.86	0.31
APRIL	720	47.7	12.5	0.44	0.97	0.12
MAY	744	58.4	10.7	0.37	1.03	0.06
JUNE	720	67.4	10.8	0.32	0.79	0.06
JULY	744	71.9	8.7	0.25	0.66	0.03
AUGUST	744	68.1	7.0	0.24	0.71	0.01
SEPTEMBER	720	62.3	9.6	0.31	0.85	0.07
OCTOBER	744	51.0	8.5	0.35	0.68	0.09
NOVEMBER	720	36.3	10.7	0.47	0.86	0.27
DECEMBER	744	25.4	8.5	0.50	0.80	0.37
YEAR	8760	46.4	10.1	0.40	1.03	0.01

Table 6.

MEASURED AIR INFILTRATION RATES
IN THE NORTHERN HOME

TEST NO.	WEATHER CONDITIONS DBT/WS/WD	INDOOR TEMP, °F	MEASURED INFILTRATION RATES	
			SCFM	ACPH
SOLARIUM CLOSED				
1-1	34/10/SW	74	204	0.44
1-6	40/15/SW	70	235	0.51
1-8	47/21/S	73	373	0.81
2-1	0/13/W	62	315	0.70
2-4	7/15/W	67	306	0.66
3-1	31/ 8/W	65	178	0.38
SOLARIUM OPEN				
1-7	44/13/S	72	426	0.81
2-3	6/15/W	65	382	0.73
3-2	38/ 9/NW	67	160	0.31

The previous discussion makes quite clear that understanding the impact of air infiltration on indoor air quality requires an enormous amount of air infiltration data from a home. Such extensive and comprehensive measurements of air infiltration rates can be so time consuming as to be prohibitively expensive. While the passive measurement approach may reduce such costs, the need for an alternative approach, i.e. a comprehensive and accurate but practical model, has been indicated as far back as 1957.⁸

It is necessary at this point, that a brief account of sources, emissions and indoor air contaminant concentrations be presented, before the potential utility of these models to the understanding and control of indoor air quality can be properly assessed.

2. Sources, Emissions, and Indoor Air Quality

The effects of air pollution on human health and welfare have been a major national concern. The main emphasis to date has been directed to outdoor sources and outdoor contaminant concentrations. As a result, Source Emission Standards and National Ambient (Outdoor) Air Quality Standards have been in force since the early 1970's covering several air contaminants such as carbon monoxide (CO), nitrogen dioxide (NO₂), particulate, photochemical oxidants (such as ozone), and hydrocarbons.

As implementation of the above standards followed its natural course, attention shifted to the indoor environment. As early as 1972 and 1974, ASHRAE co-sponsored the first two conferences in the U.S. on Indoor Air Quality, organized and administered also by Engineering Foundation Conferences.^{9,10} These have been followed, in most recent years, by other more comprehensive, national¹¹ and international¹² workshops, symposia and conferences, which signify enhanced current interest.

A recent summary assessment³ of the factors affecting indoor concentrations of air contaminants from the operation of fossil-fueled appliances is shown in Figure 1. This figure illustrates the many and complex issues needing to be addressed towards the understanding and control of indoor air quality, under realistic conditions. One such example may be "sources", such as space heating appliances and equipment to be found in the home. These can be represented by:

- Various types of kerosene heaters.
- Various types of unvented gas space heaters.
- Wood burning equipment, such as open fireplaces and wood stoves.

FACTORS AFFECTING INDOOR CONCENTRATIONS FROM COMBUSTION APPLIANCES

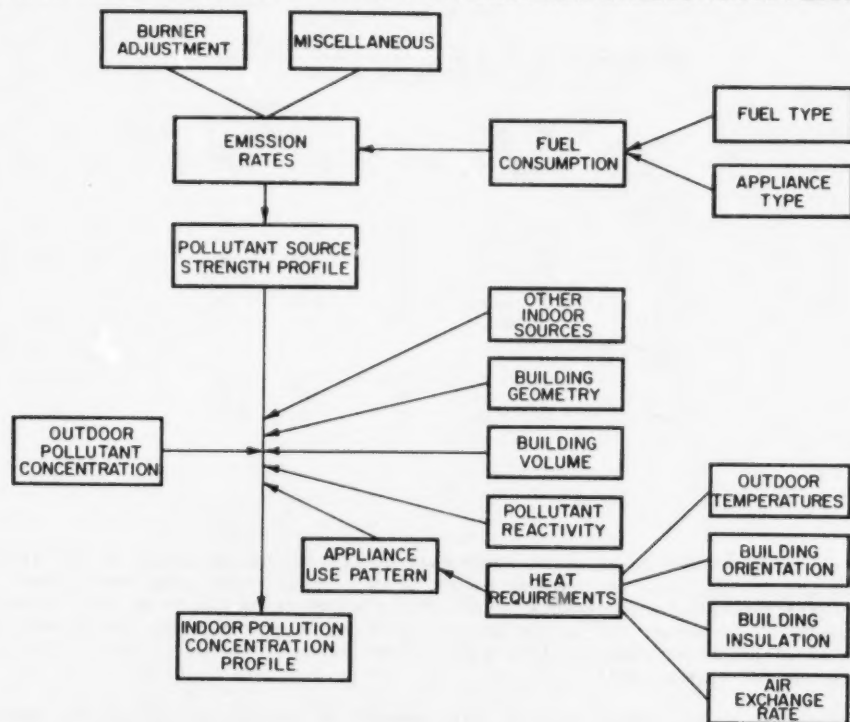


Figure 1.

Table 7 summarizes emission levels of contaminants produced in such equipment, per unit energy input, as a function of the type of fuel burned.¹³ Table 7 illustrates how little leakage into the indoor environment (from otherwise vented fireplaces and stoves) might it take to swamp the effect of emissions from any other unvented appliance in the home.

Table 7.
COMPARISON OF EMISSIONS FROM SELECTED
RESIDENTIAL SPACE HEATING SYSTEMS

SOURCE	EMISSIONS, lb/10 ⁶ Btu					$\mu\text{G}/10^6 \text{ Btu}$ B(a)P
	CO	NO _x AS NO ₂	SO _x AS SO ₂	TSP		
GAS	0.02	0.08	0.0006	0.02		80
OIL	0.04	0.09	0.3-7	0.07		900
COAL	3.50	0.10	0.5-7	0.60		2,500,000
WOOD - F	3.00	0.25	--	1.30		45,000
WOOD - S	22.00	0.07	0.03	1.20		135,000

The local, time-averaged concentration of internally generated contaminants is not only a function of the source strength but of the source's schedule of operation and indoor-outdoor relationships. Table 8 compares ranges of steady-state (peak) contaminant concentrations and 1-hour average concentrations from actual homes using kerosene heaters. The peak levels were maintained over long periods (4-6 hours) in a study of 13 field homes,¹⁴ while the 1-hour averages were obtained during the study of a "controlled" test home, using similar heaters.³

Table 8.
POLLUTANT CONCENTRATIONS FROM FIELD HOMES
WITH KEROSENE HEATERS

	YALE	WESTON
	13 HOUSES (Peak Levels)	1 HOUSE (Maximum one hour average)
BLUE FLAME HEATERS		
NO ₂ PPM	0.07 - 0.15	0.08 - 0.14
CO PPM	3.0 - 19.0	9.4 - 25.3
SO ₂ PPM	0.07 - 0.22	0.03 - 0.10
CO ₂ %	0.21 - 0.37	0.39 - 0.75
WHITE FLAME HEATERS		
NO ₂ PPM	0.08 - 0.31	0.21 - 0.38
CO PPM	0.0 - 3.4	2.6 - 6.2
SO ₂ PPM	0.03 - 0.65	0.07 - 0.10
CO ₂ %	0.33 - 0.54	0.82 - 1.09

The combined impact of changing ambient NO and NO₂ concentration, and of gas range operation, on indoor concentrations of NO and NO₂, in a California field home, is shown in Figures 2 and 3. The rapid increase of ambient NO concentration (Figure 2) starts at sunset, as the photochemical oxidation of ambient NO to NO₂ ceases in the absence of sunlight. Conversely (Figure 3) and simultaneously, the high concentration of ambient NO₂, during the daytime hours, rapidly decreases beginning with the time of sunset.¹⁵ The relative influence of these changing concentrations on the respective peak-heights of NO and NO₂, produced by the normal operation of the gas range, is quite evident.

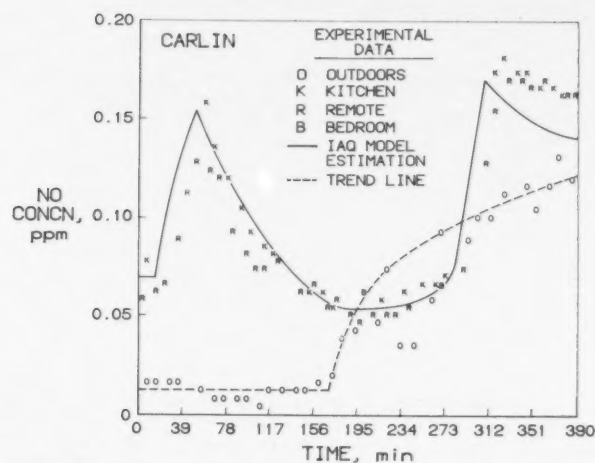


Figure 2. Outdoor effect on whole house no concentration

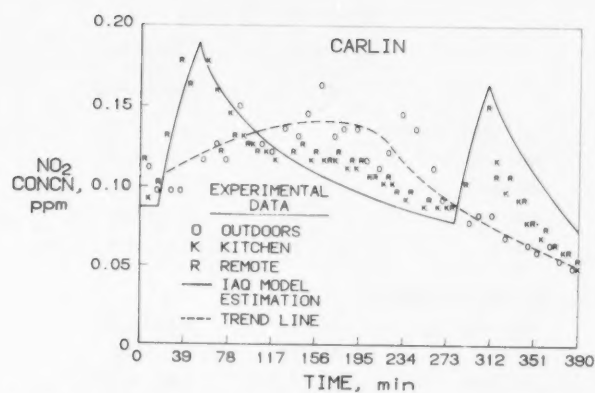


Figure 3. Outdoor effect on whole house no₂ concentration

The local concentrations of internally generated air contaminants is also much more strongly dependent on the level of communication between the various zones of the dwelling than on the whole house air infiltration rate. Table 9 illustrates 1-hour average and steady-state (peak) contaminant concentrations in a room heated by a kerosene space heater with the door open and communicating with the rest of the house, the door left ajar and closed.³

Table 9.

PREDICTED EXPOSURE CONCENTRATIONS
DURING HEATER USE

POLLUTANTS	DOOR OPEN		DOOR AJAR		DOOR CLOSED	
	DYNAMIC	SS	DYNAMIC	SS	DYNAMIC	SS
CO, PPM	4.18	4.66	9.02	9.18	19.54	19.70
NO ₂ , PPM	0.06	0.07	0.12	0.13	0.23	0.25
CO ₂ , %	0.13	0.15	0.31	0.30	0.63	0.65

The impact of zone communication is also amply illustrated in Figures 4 and 5 which show NO and NO₂ concentrations in the kitchen, bedroom and another remote from the kitchen location in a typical Chicago split-level home with basement.¹⁶ Distinctly different levels of NO and NO₂, due to gas cooking, are shown between the kitchen and other locations. Conversely, similar data (Figure 6 and 7) from a typical California ranch home (with ample interior communication) show practically no difference in the concentration levels from room to room.¹⁵

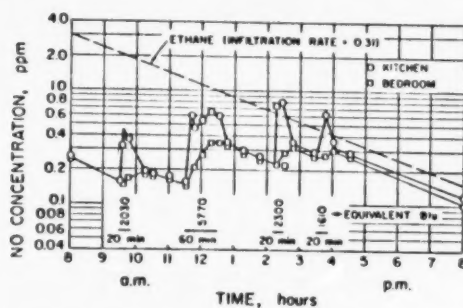


Figure 4. Continuous no monitoring in the glenwood home

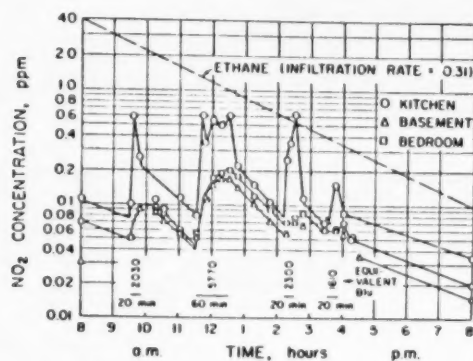


Figure 5. Continuous no₂ monitoring in the glenwood home

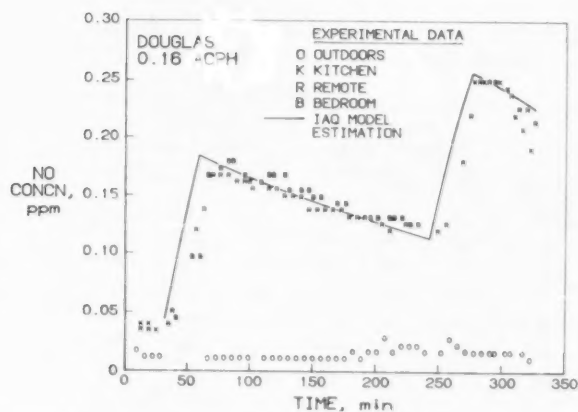


Figure 6. Gas cooking and whole house no concentration

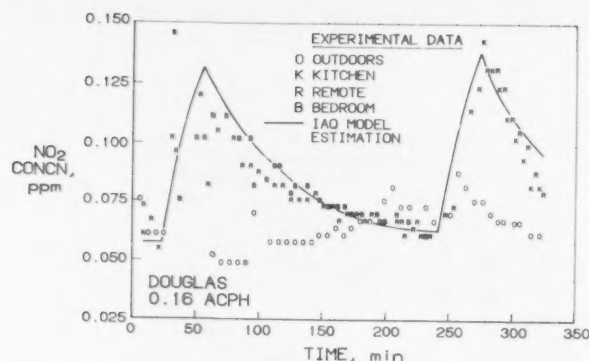


Figure 7. Gas cooking and whole-house NO_2 concentration

Another significant factor in air contaminant distribution within the home is the existence, fan capacity and schedule of operation of the central air distribution system in the home. The quality of installation of the central air distribution system (level of leakage at duct joints, duct location, etc.) also can effect air contaminant levels and the whole house rate of air infiltration. Tables 10 and 11 illustrate quantitatively how communication between the furnace room and the rest of the house depends on the operation or setting of the air distribution system.¹⁷

Table 10, for example, illustrates that under certain circumstances (furnace registers taped, fan operating), flow of air counter to buoyancy (from house to basement, where furnace is located) can take place. Table 11 (which relates to performance of a test home under constant house air infiltration rate) shows that under certain conditions (fan operating with furnace registers open), the rate of air circulation within the home can be 2 to 3 times larger than the rate of air infiltration into the home from outdoors.

Table 10.

MEASURED COMMUNICATION BETWEEN FURNACE ROOM AND HOUSE (GKC Final Report)

HOUSE ID	AIR FLOWS, SCFM					
	FAN-OFF FURNACE ROOM REGISTERS TAPED			FAN-ON FURNACE ROOM REGISTERS TAPED		
	F_{12}	F_{21}	F	F_{12}	F_{21}	F
N	0	103	253	128	206	256
O	14	58	137	116	207	166
A	11	44	106	136	153	122
B	14	75	132	286	460	218
MI	20	36	157	113	125	176
MA	21	32	153	191	234	134

F_{12} - Flow of air from house to furnace room.

F_{21} - Flow of air from furnace room to house.

F - Total house exfiltration.

Table 11.

MEASURED COMMUNICATION BETWEEN
FURNACE ROOM AND HOUSE
(GKC Final Report)
HOUSE N

	AIR FLOWS, SCFM		
	F_{12}	F_{21}	F
FOF/RT	0	103	253
FON/RT	128	206	256
FOF/RO	15	111	241
FON/RO	623	687	241

F_{12} - Flow of air from house to furnace room.

F_{21} - Flow of air from furnace room to house.

F - Total house exfiltration.

3. Modeling of Air Infiltration

In contrast to the dynamic models available for heat transfer by radiation, conduction and convection through the building envelop, early models of air infiltration have been either primitive, extremely limited and not comprehensive. A review of available models in the U.S. and Canada, before 1979, has been published¹⁸ and, therefore, would not be addressed here. Since that time, however, significant efforts have been undertaken, in the U.S. and abroad, toward the development of relevant and comprehensive mathematical models and, at least, 14 such models have been reviewed in a 1982 publication.¹⁹

The details of IGT's air infiltration model have been published¹⁸ earlier, as has its application to the simulation of air infiltration in existing homes.²⁰ Partial verification of this model by Persily and Linteris²¹ has been published in the ASHRAE Transactions. Most recently, a validation and comparison of 12 different air infiltration models, with actual data from 3 test homes (Canadian, Swiss and British), was published.²²

The results of this comparative evaluation are summarized in Table 12. Of the 12 models, 7 use complex multicell (M) mathematical formulations while the other 5 use a single cell(s) basic approach. The numbers under the heading "DATA SETS" indicate the percent of time that each model was able to simulate the actual air infiltration measurements available from each of the 3 test homes, within 25 percent of the measured value.

Table 12.

AIR INFILTRATION MODEL COMPARISONS
BY AIR INFILTRATION CENTER

MODEL	CELL TYPE	DATA SETS		
		SWISS	CANADIAN	BRITISH
1. BSRIA	M	100	49	--
			63	80
2. NRC	M	100	49	--
NRC	M	56	86	87
3. IMG-TNO	M	83	--	--
4. OSCAR FABER	M	--	--	--
5. BRITISH GAS	M	--	78	67
BRITISH GAS	M	--	76	80
6. NBRI	S	83	78	--
7. IGT	S	100	76	67
8. LBL	S	100	81	80
9. BRE	S	89	73	87
10. REEVES ET AL.	S	100	57	33

The most significant conclusion, drawn from this comparative evaluation of models, is that single cell models were more successful in simulating the actual data, with the LBL²³ and IGT^{18,20} models being the most successful. It should be noted that for its operation, the LBL model requires actual pressurization data (available from the 3 test homes). The IGT model, on the other hand, requires no experimentation at the site, relying totally on standard ASHRAE crack length data, structure orientation and shielding by adjacent building or foliage, and weather data. Most of the required data can be obtained from house blue-prints, local weather station, etc.

4. Modeling of Indoor Air Quality

A basic model for describing the dynamics of air quality variations in enclosed spaces has been around for a long time in one form or another. For example, a derivation of the general equations involved was reported by Turk²⁴ in conjunction with the use of an odor test chamber in evaluating odor reducing devices or producing odor free environments, for test purposes. Sutton *et al.*²⁵ presented a theoretical analysis of an air cleaning system, in an enclosed space, for the purpose of determining air filter efficiencies. Since the Clean Air Act of 1970, similar derivations have been made for indoor air quality models, for NO_x by IGT¹⁶ and for particulate and gaseous pollutant by NBS²⁶ and by Geomet²⁷.

Currently, while the equations involved in these modeling activities are rigorous, the models tend to be imprecise or of limited applicability, unless suitable sub-models are provided for the following:

- Internal generation rates for the contaminants of interest
- Air infiltration dynamics of the structure
- Decay or disappearance rates of the contaminants of interest
- Degree of mixing within the various sections of the house.

For such a model, therefore, to reflect the performance of real homes, additional information is required (part of it derived by measurements at the site) to be integrated with the fundamental equations.

A. Internal Generation and Decay Rates

Nitrogen oxides (NO_x) and carbon monoxide (CO) are generated indoors primarily in direct proportion to the amount of unvented combustion (for example, gas cooking) taking place. A generation model, in this case, consists of a gas cooking schedule which can be measured, or conforms to average cooking schedules, as previously used at IGT.¹⁶ From past and recent studies, average NO_x and CO emission factors for gas cooking appliances are well known.^{28,29}

Nitric oxide (NO) is quite stable and its disappearance internally is almost wholly due to dilution by infiltration and exhaust. Nitrogen dioxide, on the other hand, decays significantly faster than the infiltration rate due to absorption and reaction with various media in the house. IGT¹⁶ as well as Geomet²⁷ data indicate that the internal decay rate for NO₂ is probably exponential (1st order) in nature.

B. Effect of Mixing Factor

The mixing factor in an indoor air quality model is an important but poorly understood quantity. It is usually defined as the ratio of the actual to theoretical air change rates and can vary between 0.1 and 1.0, but is normally considered³⁰ to vary between 0.1 - 0.33. It is important not only because of its effect on indoor air quality, in a ventilated space, but also because it affects the measurement of air infiltration.

The concept of the mixing factor has recently been redefined by Esman³¹ strictly in terms of a mass balance equation, and a vast improvement in data fitting ability was demonstrated by comparison to real data by Ishizu.³² The latter paper has shown that, if the mass balance equation is properly integrated, the model does in fact fit real time data much better than with the old definition of mixing factors mentioned above. As the mixing factors can be very small fractions, their effect on indoor air quality must be taken into account.

C. Integrated Air Quality/Infiltration Model

The only attempt to date at developing an integrated air quality/air infiltration model has been made by Geomet²⁷. This model has been only partially successful, primarily due to lack of a good infiltration submodel. The Geomet model utilizes a literature infiltration model modified to account for differences in the tightness of the homes. The Geomet model is an empirical one based on a modification of the Achenbach-Coblentz³³ regression analysis of infiltration data obtained in 10 electrically heated homes in the Midwest.

The Geomet model also neglects the effect of wind speed on air infiltration which affects, almost solely, infiltration in mild climates, where the indoor-outdoor temperature difference is rather small. In addition, this model does not include a mass balance around the house; this is very important for an air quality model because of the existence of common contaminants (NO_x , CO, radon) in both the indoor and outdoor air.

CONCLUSIONS

The following significant conclusions can be drawn from the previous discussion —

- The generation, dispersion and fate of potentially harmful contaminants in the indoor air are complex relationships requiring a large amount of data and information to understand them or to control the quality of indoor air.
- To gain an understanding of the role natural infiltration plays in these relationships through air infiltration measurements can require an enormous quantity of detailed and comprehensive data as to be non cost-effective.
- Since natural infiltration is going to be a prime mechanism for indoor air quality control, in the residential structures of the next generation, comprehensive but practical and cost effective air infiltration models are more suitable alternatives.
- The need for interactive, multi-cell approaches to modeling indoor air exchange is imperative. Such approaches can be couple with existing single cell air infiltration models to develop more comprehensive indoor air quality models.
- Point source venting of undesirable contaminants can be more efficient, energy conservative and cost effective than other approaches, such as whole-house air-to-air heat exchangers, that operate with highly diluted products.
- Use of an air-to-air heat exchanger can be justified only on a retrofit basis, for safety reasons, as for example in a tight dwelling with a proportionally large open fireplace and associated chimney, that can counter proper venting of fossil-fueled equipment.
- Finally, proper selection of indoor air quality control mechanisms and equipment cannot be made in the absence of comprehensive indoor air quality models which have been verified under "real world" conditions.

ACKNOWLEDGEMENT

I wish to recognize the work of my colleagues over the years at IGT from which material for this paper was obtained. In particular, I wish to recognize Tim Cole, Bob Elkins, Vince Huang and Tom Zawacki.

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Effects of Different Ventilation Parameters on Indoor Pollutants

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ABSTRACT

For controlling and for setting ventilation standards to maintain acceptable indoor air quality, it would appear to be of greatest importance to determine the strength of relationships between contaminant concentrations on one hand and different rates of ventilation and how these rates are expressed on the other.

Important data to do just that are now available and are contained in a computer stored archive of building investigations of indoor air quality conducted in Canada and the U.S. This archive contains adequate ventilation information for 21 instances for comparing pollutant concentrations under various ventilation conditions.

Four observations emerge from the analysis of these data:

1. Some ventilation measures are more sensitive to occupancy requirements than are others.
2. Pollutants respond differently to ventilation. No one pollutant can serve as a predictor of overall indoor air quality.
3. Air quality may be largely building dependent. Buildings maintain an ambient level of contaminants based on configuration, location, indoor activities, occupancy, materials, equipment and maintenance. Once a building is operational, manipulation of ventilation may have only a small impact on the base level of indoor pollutants.
4. Current practice in ventilation system design may under-estimate actual occupancy loads.

INTRODUCTION

Existing ventilation standards are based on the need to maintain acceptable air quality in modern tightly sealed buildings. Until ten years ago, the most widely preferred strategy of reducing levels of indoor contaminants was by dilution with fresh (makeup) air from outdoors and, of course, ample use of filters. However, increased energy costs for heating and cooling makeup air have made the option of dilution less attractive. (ASHRAE, 1982) Reductions in both ventilation and energy use have been accompanied by increasing health and comfort complaints among occupants. An epidemic called Building Illness, or Office Building Syndrome, has been identified which refers to complaints of illness, including headache, burning eyes, irritation of the respiratory system, drowsiness and fatigue. The symptoms are generally experienced over an extended period of time and recur during occupancy in sealed buildings. The causes are rarely definitely determined, but suspected to be related to components of the building or air supply system. (Hicks, 1983; Sterling *et al*, 1983)

This relation is implicitly acknowledged by attempts to regulate the quality of indoor air, especially the concentration of pollutants by manipulating ventilation standards. But to do so requires more knowledge about (1) how different ventilation parameters (ways of measuring

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ventilation) are related to each other in practice, and (2) how different ventilation parameters are related to concentrations of gaseous and particulate components of indoor air.

Ventilation is expressed in a large variety of measurements. The most widely used measures are Air Changes per Hour (ACH) and Cubic Feet per Minute (CFM) or Litres per Second (L/S). ACH is the measure of total air exchange in an enclosed area based on time, while CFM (L/S) is a volumetric measurement of air movement. Requirements for ventilation of enclosures listed in Table 3 of the ASHRAE standard 62 - 1981 are calculated on the basis of occupant density (CFM/person, L/S.person), and in some cases based on other variables, such as floor space or number of beds in hospitals. The Total amount of air supplied or CFM (Total Supply Air) is a mixture of Recirculated air, or CFM (Recirculated Air), and Fresh outside air, or CFM (Fresh Makeup Air). However, it is not often known what the occupant load will be over the life of the building. For this reason, occupant load is often predicted on a square foot basis. The standard prediction factor is one person per 180 sq. ft. (Leaney, 1983)

As a consequence, a number of ventilation parameters are designed into the building to satisfy estimated ventilation requirements. The basic, designed-in parameter is CFM (Total Supply Air). The amount of CFM (Fresh Makeup Air) and CFM (Recirculated Air) are regulated by use of dampers, and at all times they are related as $\text{CFM (Total Supply Air)} = \text{CFM (Fresh Makeup Air)} + \text{CFM (Recirculated Air)}$.

Designed-in CFM (Total Supply Air) will of course vary with the size of the building, its basic characteristics, number of occupants, its location, and other expectations of use and performance. In general, CFM (Total Supply Air) will be larger with larger buildings that will be expected to have greater use and occupancy than smaller buildings with less anticipated use and occupancy. However, any standard setting attempt needs to be aware of the degree to which these designed-in ventilation parameters correlate with each other and with parameters affected by actual use and occupancy.

There are of course a number of ventilation parameters that can be defined by expressing total, fresh and recirculated air with respect to actual occupancy and activities in the building. Perhaps the most important are ventilation parameters related to actual occupancy. These can be expressed as an operational CFM/PERSON (Total Supply Air) CFM/PERSON (Fresh Makeup Air) and CFM/PERSON (Recirculated Air), where $\text{CFM/PERSON (Total Supply Air)} = \text{CFM (Total Supply Air)} / \text{number of occupants}$, $\text{CFM/PERSON (Fresh Makeup Air)} = \text{CFM (Fresh Makeup Air)} / \text{number of occupants}$, and $\text{CFM/PERSON (Recirculated Air)} = \text{CFM (Recirculated Air)} / \text{number of occupants}$.

The current ventilation standard (ASHRAE 62-1981), as its predecessor (ASHRAE 62-73), is based primarily on chamber studies such as those conducted in the 1930's by Yaglou *et al* (1936) or more recently by Cain *et al* (1983). Results were reported in CFM/PERSON of fresh air ventilation needed to provide "odor free" environments (Woods, 1979). In the 50 years since the Yaglou studies, significant advances have occurred in both air quality and ventilation measurement technology. Also in the past 10 years, both ventilation and air quality have been measured simultaneously in investigative studies of many modern sealed buildings. For controlling and setting ventilation standards to maintain acceptable indoor air quality, it would appear to be of greatest importance now to determine:

1. the strength of relationships between ventilation and contaminant concentrations, and
2. the most effective measure of ventilation for the purpose of air quality control.

In 21 cases where adequate data exist for ventilation and air quality we examine relationships among different ways of measuring ventilation and between these possible measures of ventilation and observed concentrations of gaseous and particulate air contaminants.

METHOD

A large number of office buildings have been investigated during the last few years in order to determine the relationship of indoor pollutants either to health and comfort complaints of occupants or to building characteristics. At the time of this report, 143 such studies had been reviewed and information contained in them placed in a computer based Building Performance Information System (BPIS). Contained in this data base are 21 instances in which investigators provided information on ventilation characteristics of the buildings analyzed as well as levels of some key pollutants. That information was extracted from BPIS and prepared for further analysis.

Ventilation characteristics were obtained either as they were stated in or calculated from information in each report. Measured characteristics include: percent of fresh air, percent of

recirculated air, CFM (Fresh Makeup Air), CFM (Recirculated Air), CFM (Total Supply Air), CFM/PERSON (Fresh Makeup Air), CFM/PERSON (Recirculated Air), CFM/PERSON (Total Air Supply), Total Air Changes per Hour (TACH), Fresh Air Changes per Hour (FACH), and number of individuals occupying a space (Population).

An adequate number of these studies also measured the same pollutants so that their analysis could be included. These were carbon dioxide, carbon monoxide, particulates, and hydrocarbons.

The results of analysis of these data are presented in three sections. First, the intercomparison between the different ventilation measures; second, the relationship between ventilation and pollutant concentrations across buildings and third, the relation of pollutants to ventilation measures in specific buildings.

Results Part I: Intercomparison Between Ventilation Measures

Table 1 summarizes results of correlating major ventilation parameters across buildings for which these measures can be computed (using Pearson Product Moment Correlation Coefficients). It is immediately apparent that designed-in parameters CFM (Total Supply Air), CFM (Fresh Makeup Air), and CFM (Recirculated Air) are highly intercorrelated as would be expected. After all, they are determined by the same requirements dictating the properties of ventilation systems. On the other hand, intercorrelations fail to be significant between most designed-in parameters and parameters relating to actual use. However, these latter are again highly intercorrelated.

CFM (Total Supply Air) is significantly and highly correlated to both CFM (Fresh Makeup Air) ($r = .89$) and CFM (Recirculated Air) ($r = .99$). That is, as CFM (Total Supply Air) increases, so does CFM (Recirculated Air) and CFM (Fresh Makeup Air). While CFM (Fresh Makeup Air) is correlated with CFM/PERSON (Fresh Makeup Air) ($r = .41$) and Population ($r = .56$), it is not significantly related to CFM/PERSON (Total Supply Air) or CFM/PERSON (Recirculated Air). This lack of correlation, by itself, is an interesting finding. Among the determinants of CFM (Total Supply Air) (and with it CFM (Fresh Makeup Air)) is the expected use of the building, especially the anticipated number of occupants. Thus one would expect calculated CFM/PERSON (Fresh Makeup Air) and estimated, that is, designed-in CFM (Fresh Makeup Air) to correlate highly. Although that correlation is positive and statistically significant, it is relatively small ($r = .41$, $p = .05$). Further the correlation between CFM (Fresh Makeup Air) and CFM/PERSON (Total Supply Air) is small and not significant ($r = .31$, $p = .2$). A further clue for the complexity of these inter-relationships is offered by the negative correlation between actual occupancy and CFM/PERSON (Fresh Makeup Air). This correlation is statistically significant and negative ($r = -.37$, $p = .05$). (See Figures 1 and 2.)

Figure 1 is a scattergram of CFM (Fresh Makeup Air) by Population. Figure 2 is a similar plot with CFM/PERSON (Fresh Makeup Air) by Population. From visual inspection it can be seen that as Population increases so does CFM (Fresh Makeup Air). But a negative relation exists between CFM/PERSON (Fresh Makeup Air) and Population.

Insofar as CFM (Fresh Makeup Air) is based on an estimate of the number of people anticipated to occupy the premises, one would expect the correlation between CFM/PERSON (Fresh Makeup Air) and number of people actually present to be positive. That is, the more people are present, the larger would be CFM (Fresh Makeup Air). Now that is true in part because the correlation between CFM (Fresh Makeup Air) and Population is indeed positive ($r = .56$, $p = .01$) (See Figure 2). However, the correlation between the calculated value of CFM/PERSON (Fresh Makeup Air) and Population actually present is negative. This negative correlation indicates that while it may be true that as the number of persons expected to occupy a space increases, the amount of CFM (Fresh Makeup Air) supplied to this space also increases, yet that increase fails to be proportionate to the actual number of individuals who occupy that space once the building is built. Or, stated another way, the number of individuals who actually occupy a space tend to be consistently larger than the number of individuals who were expected to occupy that space. Thus the observed correlation between CFM/PERSON (Fresh Makeup Air) and population is negative. As one important consequence, the amount of fresh air per person appears to be constantly and, what may be more important, progressively underestimated.

Conclusion, Part I

Not all ventilation parameters measure the same aspect of ventilation. CFM (Fresh Makeup Air) and CFM/PERSON (Fresh Makeup Air) may be very different measures of ventilation. CFM (Fresh Makeup Air) is the additive, predicted fresh air requirement for a total building based on certain assumptions—heat gain from lighting, solar exposure and equipment as well as the number of occupants expected. Although heat gain increases somewhat with population, other major

sources of heat are lighting, solar radiation and working equipment. These factors do not necessarily increase with an increase in population. Ventilation engineers concerned with provision of acceptable air quality should select the most appropriate measure of ventilation as the basis for systems design. At present, CFM (Fresh Makeup Air) and CFM/PERSON (Fresh Makeup Air) are not proportionally related. Attempts at developing new standards need to take these factors into consideration.

Results Part II - Relations between Ventilation Parameters and Pollutant Concentrations

Ventilation is the primary mechanism used in modern office buildings for achieving acceptable air quality. CFM (Total Supply Air) and CFM/PERSON (Total Supply Air) are the most widely used measures of ventilation. Table 2 shows the correlation between these ventilation measures, CFM (Total Supply Air) and CFM/PERSON (Total Supply Air) with, levels of carbon dioxide, carbon monoxide, particulates and hydrocarbons. The correlation between CFM (Total Supply Air) and carbon dioxide is negative and significant ($r = -.85, p \leq .01$). As total air supply increases, carbon dioxide decreases. However, the correlation between CFM (Total Supply Air) and hydrocarbons is positive and significant ($r = .85, p \leq .01$). As CFM (Total Supply Air) increases, hydrocarbons also increase. Neither carbon monoxide nor particulate levels appear to be related to CFM (Total Supply Air) measures. CFM/PERSON (Total Supply Air), shows significant negative correlation with carbon dioxide ($r = -.62, p \leq .05$), as does CFM (Total Supply Air). However, correlations with hydrocarbons, particulates and carbon monoxide are small and statistically not significant.

Conclusion Part II

Carbon dioxide concentrations are often used to predict the level of acceptability of indoor air. However, the existing data shows that carbon dioxide levels respond differently to changes in ventilation than do hydrocarbons, carbon monoxide and particulates (specifically to changes in CFM (Total Supply Air) and CFM/PERSON (Total Supply Air)).

Concentrations of particulates appear not to be related to CFM (Total Supply Air) and CFM/PERSON (Total Supply Air). However, concentrations of hydrocarbons (very small particles) increase significantly with CFM (Total Supply Air). The increase in concentration of very small particles could be accounted for by torn or poorly maintained filters which fail to remove smaller particles from the air supply once they are entrapped inside the building structure.

Carbon monoxide levels are unrelated to changes in ventilation parameters. Carbon monoxide and carbon dioxide are both gaseous air constituents. If major sources of both are located indoors, such as human metabolism for carbon dioxide or tobacco smoke for carbon monoxide, then they should respond similarly to all measures of ventilation. This is not the case. Carbon dioxide is reduced by increased ventilation but carbon monoxide is not. The most logical explanation is that although sources exist inside some buildings, the major proportion of carbon monoxide found indoors infiltrates the building fabric from outdoors. Measurement data from 143 buildings presented at the ASHRAE, Washington, DC, meeting (Sterling *et al*, 1983) lends support to this explanation. Levels of carbon monoxide are uniformly small, irregardless if smoking is prohibited, restricted or permitted. These findings also agree with reviews and studies in the published literature. (Sterling *et al*, 1982, 1983) Carbon monoxide levels measured indoors primarily reflect outdoor not indoor sources. (also shown in Yocum, 1982)

Results Part III - Relation of Pollutants to Ventilation Measures in Specific Buildings

Three studies in the sample monitored pollutant levels simultaneous with manipulation of ventilation rates. Pollutants that have been consistently measured include carbon dioxide, carbon monoxide, particulates and hydrocarbons.

Table 3 presents consolidated results of three such studies. Here the relation of pollutant levels with variations of ventilation rates can be seen within the same building. Table 3 presents ventilation measures as they could be determined from the reports obtained from the investigators. Turiel *et al* (1981) measured indoor levels of carbon dioxide, hydrocarbons, particulates, and carbon monoxide in a new San Francisco office building under both 15% and 100% fresh air conditions. Berk *et al* (1979) measured carbon dioxide and carbon monoxide in a new high school under 5.1%, 8.4% and 45% fresh air conditions. Salisbury *et al* (1979) measured carbon dioxide, carbon monoxide and particulates on six different floors of a 36 story new office building in Atlanta. Ventilation conditions varied from 13.2 to 29.5% fresh air. For Berk *et al* and Salisbury *et al* Table 3 only includes lowest and highest fresh air conditions for purposes of comparison.

In all three cases, with increased fresh air ventilation, the only significant reduction in

pollutant levels occurred for carbon dioxide. The carbon dioxide level decreased when percent of fresh air increased. All other contaminants maintained a steady level within each building. Carbon monoxide reflected outdoor levels at all times. Both findings are consistent with results of Part II where relation of measured pollution levels with ventilation increases were compared across buildings.

Conclusion Part III

These data indicate that an asymptotic relation very likely exists for contaminants found in modern buildings. Contaminant levels measured tend to be building dependent. Buildings maintain base levels of commonly measured pollutants. Increased ventilation reduces the level of carbon dioxide slightly and may have a similar effect on other indoor generated contaminants. On the other hand, other contaminants measured, including carbon monoxide and particulates, respond more to outdoor levels than to indoor sources. In specific buildings with large occupancy levels and small volumes increased ventilation may be an effective means of reducing carbon dioxide and other indoor-generated contaminants to acceptable levels. However, a better means for controlling carbon monoxide and particulates would appear to be filtration of outdoor air.

CONCLUSIONS

These data are only the beginning of a review of actual building ventilation system performance which must be undertaken as basis for a new consensus ventilation standard. We have seen that:

1. Some ventilation measures are more sensitive to occupancy requirements than are others.
2. Pollutants respond differently to ventilation, no one pollutant can serve as a predictor of overall indoor air quality,
3. Air quality may be largely building dependent. Buildings maintain an ambient level of contaminants based on configuration, location, indoor activities, occupancy, materials, equipment and maintenance. Once a building is operational, manipulation of ventilation may have only a small impact on the base level of indoor pollutants.
4. Current practice in ventilation system design may under-estimate actual occupancy loads.

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Table 2: Product Moment Correlations of Total CFM and Total CFM/Person with Levels of Commonly Measured Indoor Air Pollutants from 21 Case Studies

POLLUTANT	CFM (TOTAL)		CFM/PERSON (TOTAL)	
	r	p	r	p
CARBON DIOXIDE	-.85	<.01	-.62	<.05
CARBON MONOXIDE	-.07	-	-.13	-
PARTICULATES	+.06	-	-.20	-
HYDROCARBONS	+.85	<.01	+.31	-

- not significant

Table 3: Comparison of Pollutant Levels with Ventilation Measures in Three Building Air Quality Investigations

VENTILATION PARAMETERS	TURIEL et al*		BERK et al*		SALISBURY et al*	
	A	B	A	B	A	B
% FRESH AIR	15	100	5.1	45	13.2	25.9
% RECIRCULATED AIR	85	0	94.9	55	86.8	74.1
POLLUTION MEASURES						
CARBON DIOXIDE ppm	976.0	645.8	1275	850	650	600
CARBON MONOXIDE ppm	<4	<4	4.5	4.5	4.75	3.25
HYDROCARBONS ppm	2.5	0.56	-	-	3.55	3.31
PARTICULATES mg/m ³	.031	.021	-	-	.023	.024

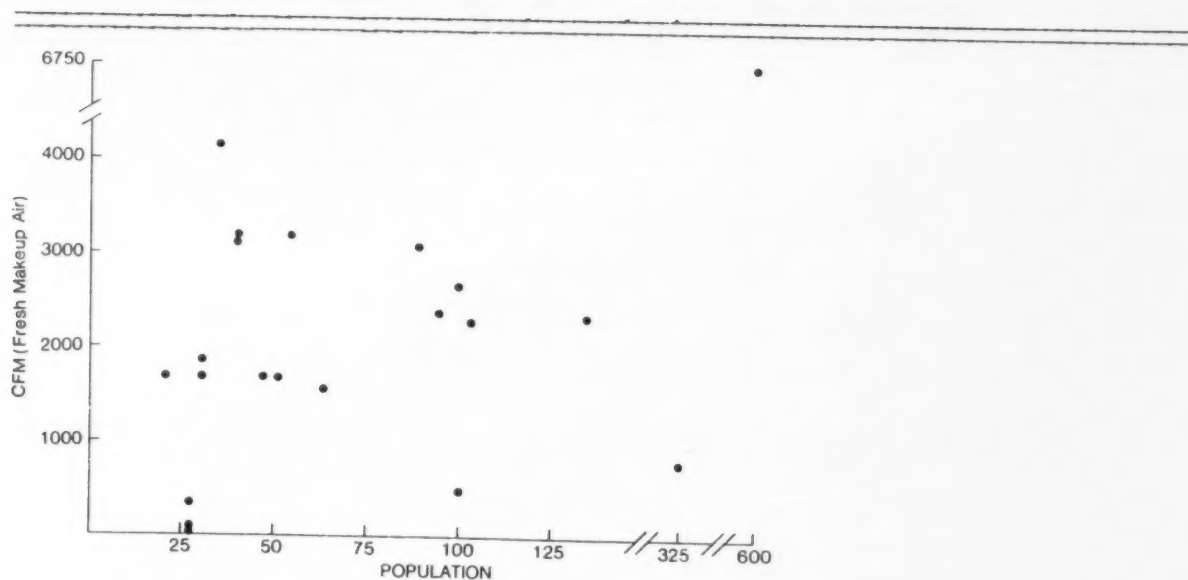


Figure 1. Scattergram of CFM (fresh makeup air) by population

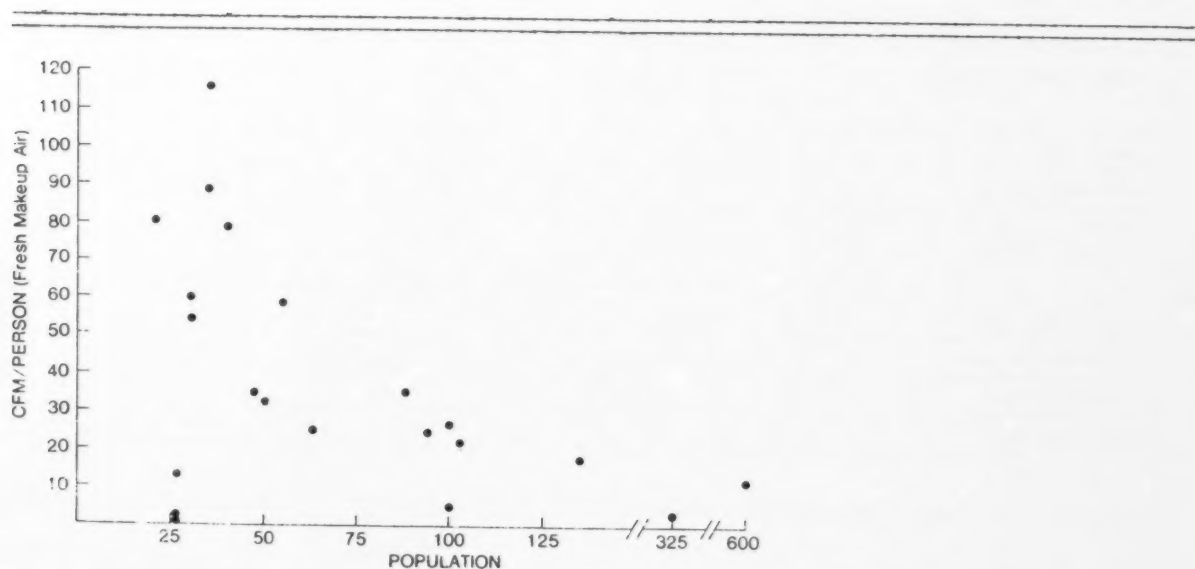


Figure 2. Scattergram of CFM/Person (fresh makeup air) by populations